Search for New Physics in the Multijet final states at CMS

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Outline

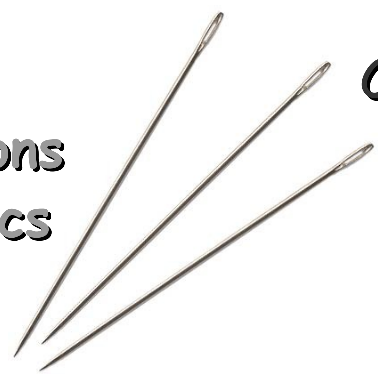
Exotic searches with

multijet (n ≥ 1) signature

and/or **MET** (missing E_T) :

- Jet identification in CMS
- CMS 2011 searches based on > 1/fb of the proton-proton LHC data

SUSY
Extra Dimensions
Strong Dynamics
... ?



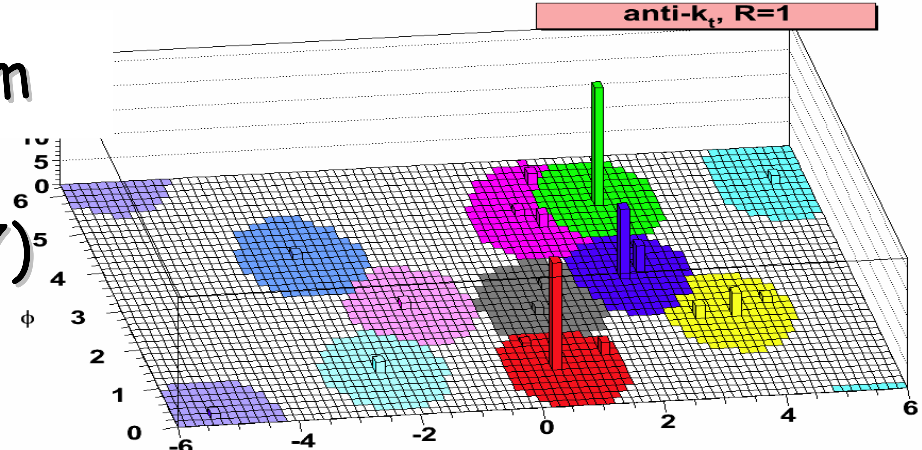
CMS searches in all-hadronic channels for:
ADD ED (monojets),
exited quark, quark compositeness, Z',
RS graviton (dijet resonances),
and microscopic black holes (multijets)

Jet reconstruction in CMS

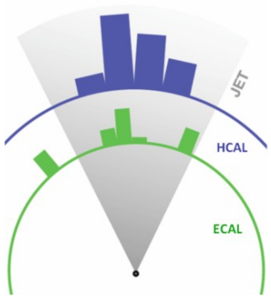
- Clustering by anti-k_T algorithm

  (infrared and collinear safe)

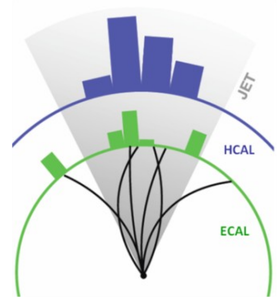
  with cone size $R = 0.5$ (or 0.7)

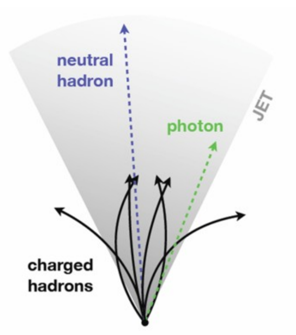


- Jet objects:



  - **Calorimeter Jets** build on calo cluster form HCAL & ECAL
  - **Jet Plus Tracks** Calo Jets corrected using the tracker information → improved energy and direction measurements

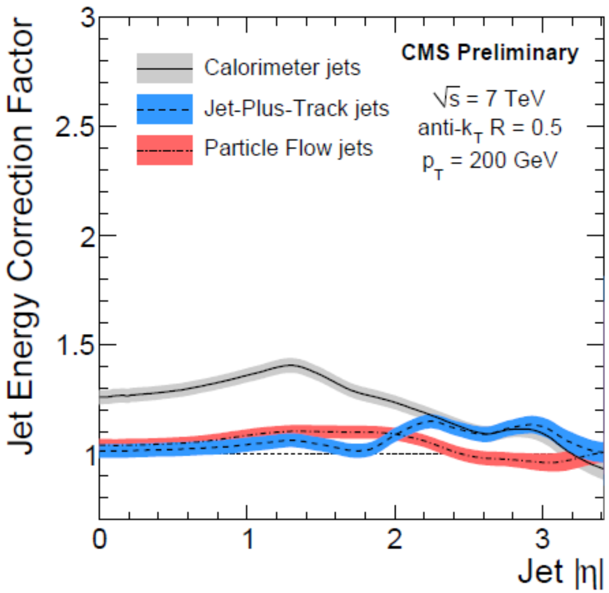


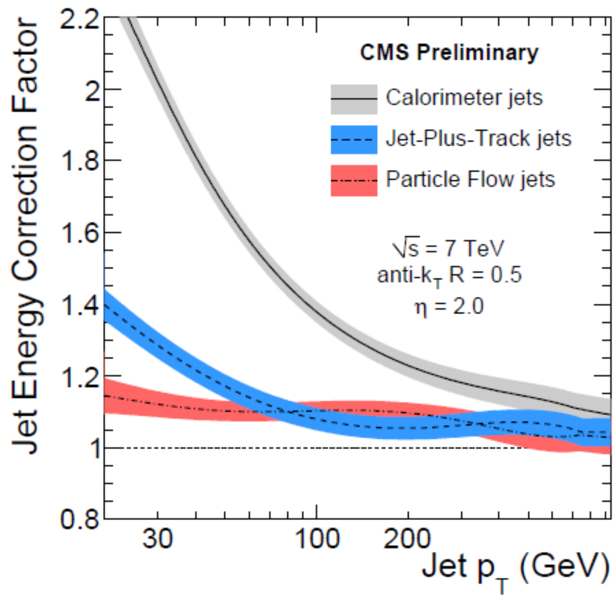


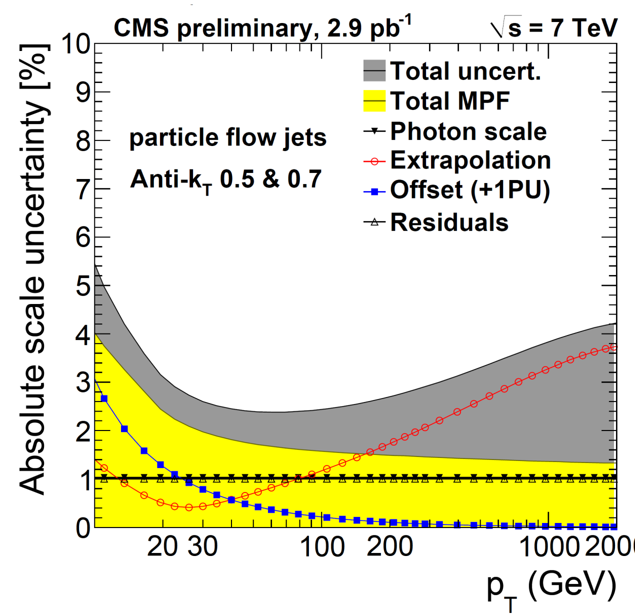
  - **Particle Flow jets (PF jets)** PF algo reconstructs and identifies all particles in a given event by an optimal combination of all deposits from sub-detectors; then particles are clustered into jets → PF Jets have the best resolution

Jet Energy Scale

[CMS PAS JME-10-010]







Jet Energy Scale (JES) Calibration

non-uniform and non-linear response of calorimeters and electronics noise and additional pp interactions in the same bunch crossing (event pile-up) can lead to extra unwanted energy

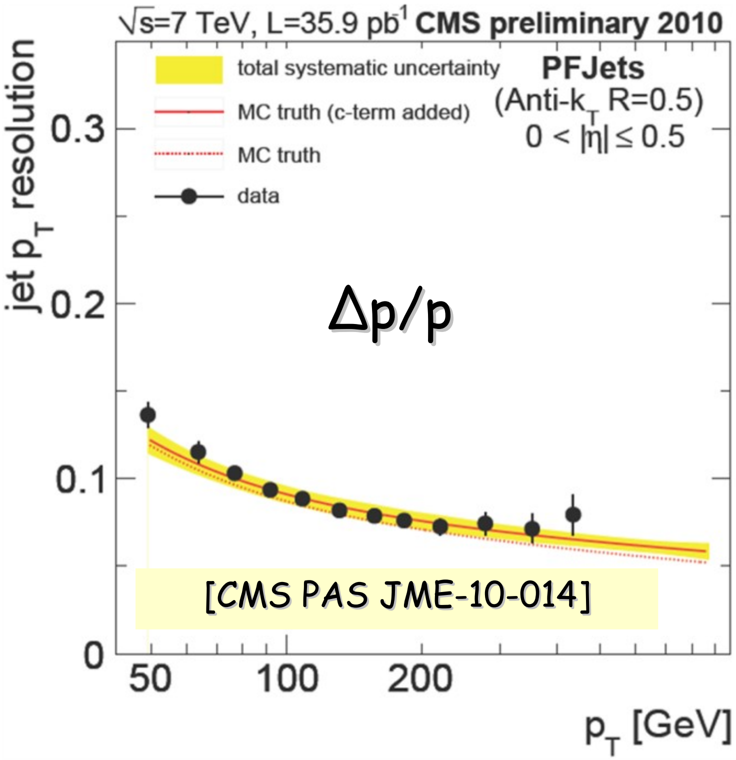
needed in order:

- to relate, on average, the energy measured in the detector jet to the energy of the corresponding real jet

3 – 6% uncertainty of the overall JES

in a wide region of jet pT from 30 (20, 15) GeV up to 2 TeV for CALO (JPT, PF) jets

Jet Resolution, HT, MET



Jet PT Resolution

measured in data and MC using data driven methods

- Dijet Asymmetry Method, which is based on the measured kinematics of the dijet events
- Photon Plus Jet Balance Method, where well measured photon pT is a reference object for the recoiling jet

Uncertainty on Jet PT resolution is about 10%

CMS variables:

- HT is a **scalar sum** of the transverse momentum of **all jets** in the event
- MET is reconstructed as a negative **vector sum** of the transverse momentum of **all particles** in the event

Monojet + MET at 1.1/fb

[CMS PAS EXO-11-059]

Large Extra-Dimension model:

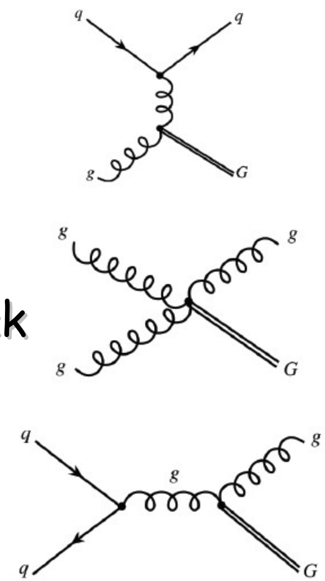
ADD ED, [Arkani-Hamed, Dimopoulos, Dvali, Phys. Lett. B 429, 263]

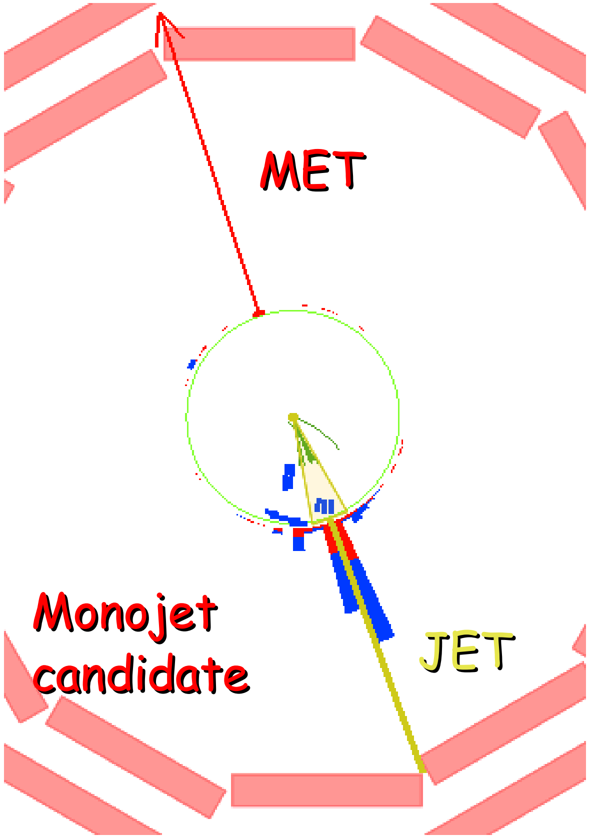
- δ extra dimensions compactified over a torus with radius R
- SM confined to "our" dimensions, gravity can propagate in LED
- **M_D scale** related to Planck mass
  - ADD parametrised by M_D, δ: $M_{PL}^2 \approx M_D^{2+\delta} R^\delta$

M_D = 1, 2, 3, 4, 5 TeV
δ = 2, 3, 4, 5, 6

Monojet signature:

- **one high pT** (~hundred GeV) jet in the central region, although 2[nd] less energetic jet is allowed
- **Large MET** (from Graviton); same magnitude as jet, typically back-to-back





Background:

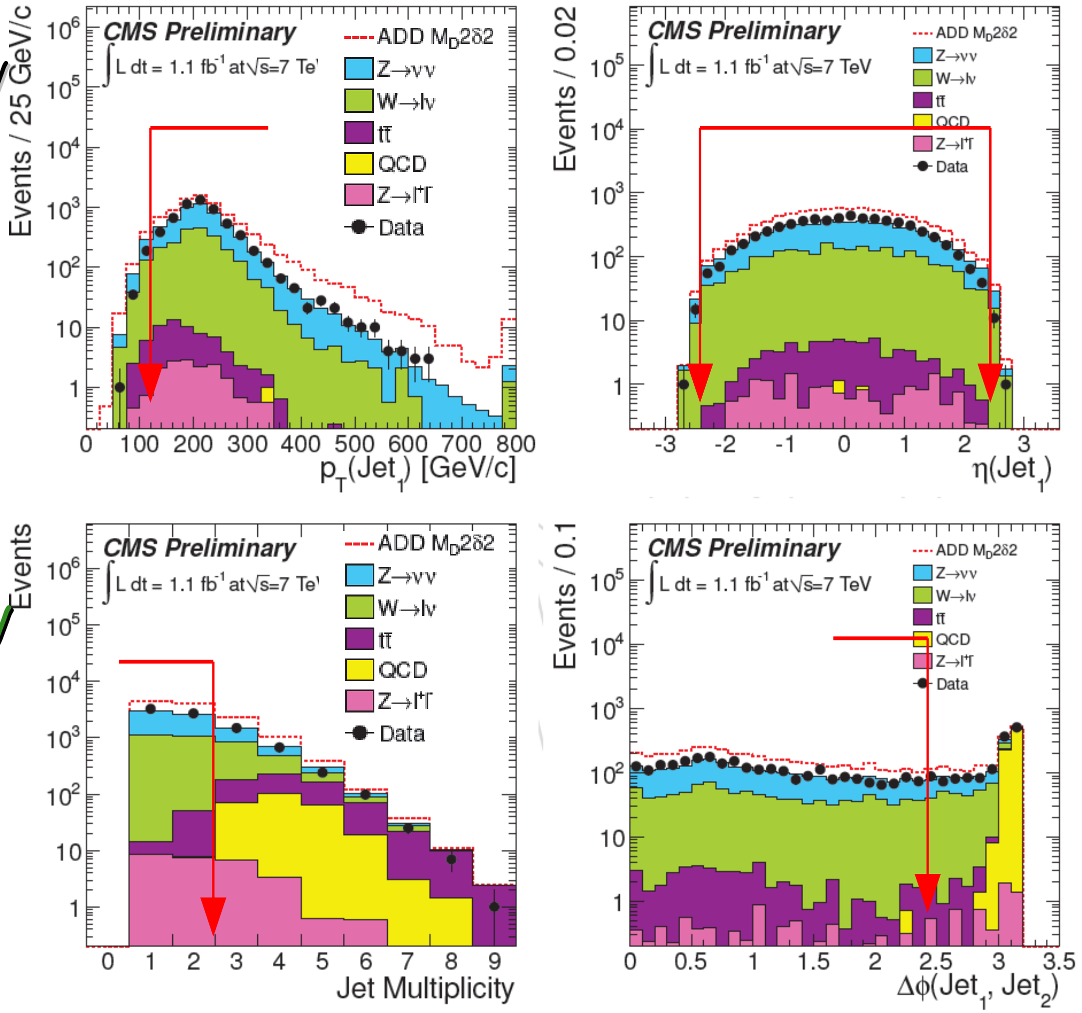
- from Z(νν)+jets, W+jets

Monojet + MET at 1.1/fb

[CMS PAS EXO-11-059]

Selection:

- Trigger on JET+MET
  Calo Jet>80 GeV, Calo MET>80 GeV
- MET > 200 GeV, jet cleaning
- 1 or 2 jets (to increase efficiency)
- $pT1 > 110$ GeV, $|\eta_1| < 2.4$
- $pT2 > 30$ GeV, $\Delta\varphi_{12} < 2.5$



Monojet Signal Sample:

- By lepton rejection
- Reject isolated e/μ pT > 10 GeV
- Track isolation veto

QCD multijet bkg. is reduced by several orders of magnitude to a negligible level using topological cuts ($\Delta\varphi12$)

Monojet + MET at 1.1/fb

[CMS PAS EXO-11-059]

Data-driven background estimation:

- Leptons have to be included
  - isolated μ with $p_T > 20$ GeV

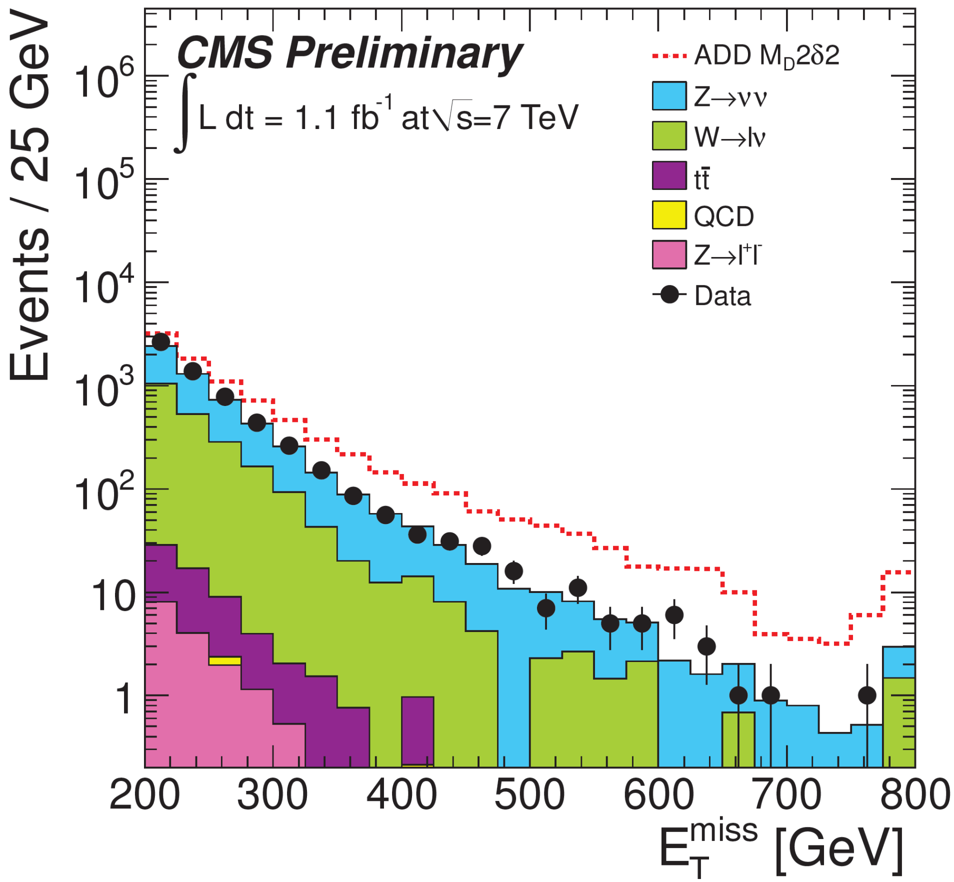
A measurement of the electroweak background from **Z(μμ)-** and **W(μν)-** enriched data is used to derive a background estimate for

Z(νν)+jets and

W+jets

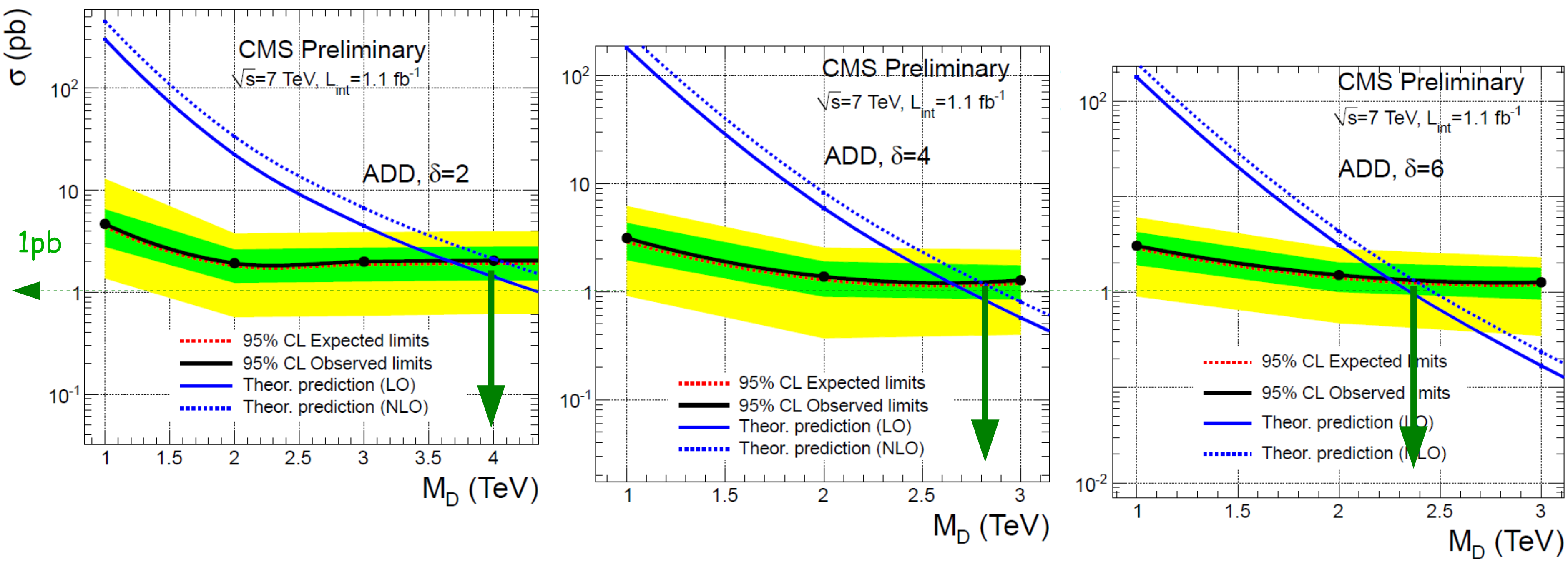
remaining in the signal region

The data are found to be in agreement with the expected contributions from SM processes



Monojet + MET at 1.1/fb

[CMS PAS EXO-11-059]



	δ	K factor	CMS 36 pb^{-1} Obs. Limit	$E_T^{miss} > 200$ GeV Exp. Limit	$E_T^{miss} > 200$ GeV Obs. Limit	$E_T^{miss} > 350$ GeV Exp. Limit	$E_T^{miss} > 350$ GeV Obs. Limit
LO	2		2.29	2.96	2.72	3.72	3.67
LO	3		1.92	2.41	2.21	3.00	2.96
LO	4		1.74	2.17	2.00	2.68	2.66
LO	5		1.65	2.02	1.87	2.44	2.41
LO	6		1.59	1.94	1.81	2.27	2.25
NLO	2	1.5	2.56	3.26	3.00	4.10	4.03
NLO	3	1.5	2.07	2.63	2.39	3.25	3.21
NLO	4	1.4	1.86	2.30	2.13	2.83	2.80
NLO	5	1.4	1.74	2.13	1.98	2.57	2.55
NLO	6	1.4	1.68	2.04	1.91	2.39	2.36

95% CL Bayesian limits on ADD model parameters extended to

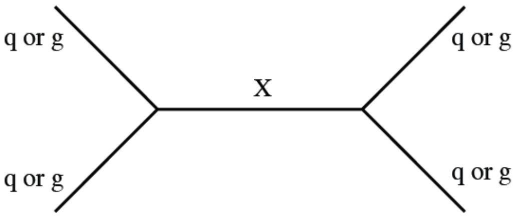
M_D > 4.03 TeV for $\delta = 2$

M_D > 2.36 TeV for $\delta = 6$

Dijet Resonances at 1.0/fb

[CMS PAS EXO-11-015]

- Many models of New Physics predict resonance decaying into dijets
- **Signature:**
  narrow dijet resonance
  in the dijet mass spectrum



Event selection:

- Trigger based on HT > 550 GeV
- At least 2jets with $|\eta| < 2.5$ & $\Delta\eta_{12} < 1.3$
- Events with dijet invariant mass M > 838 GeV are selected without any requirements on pT of leading jets

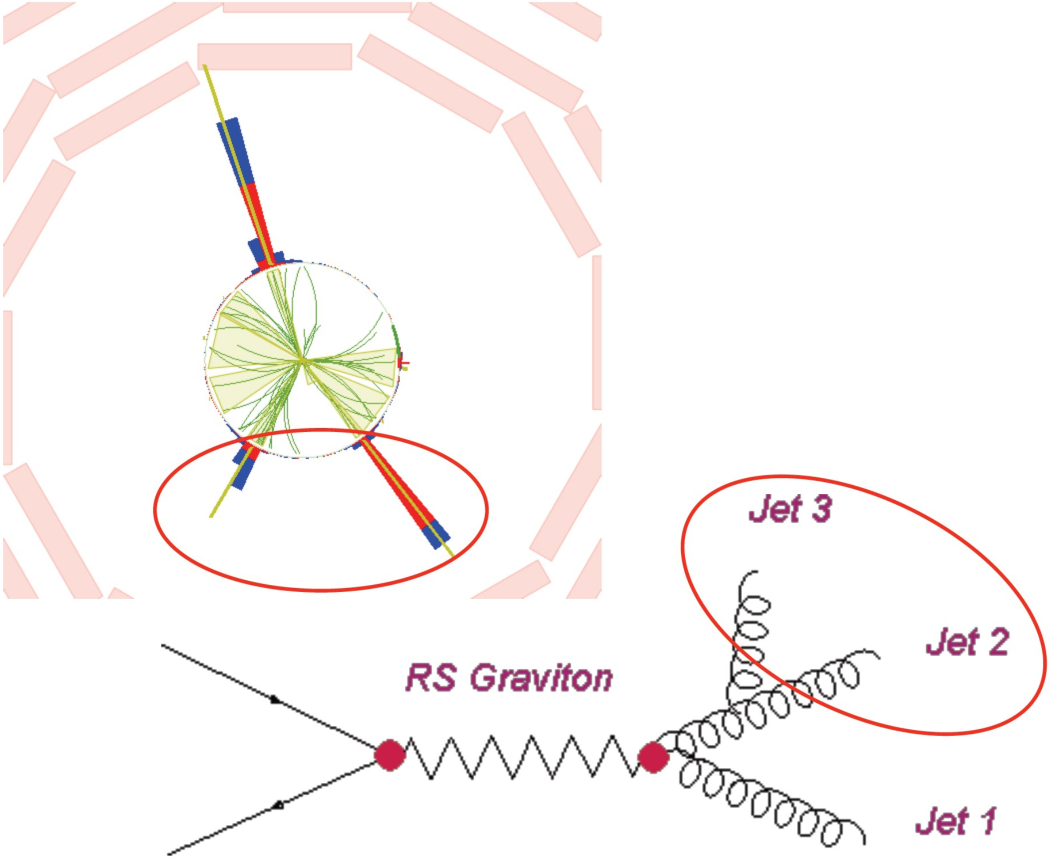
Models	X	Color	J^P	$\Gamma/(2M)$	Chan
Excited quark	q*	Triplet	$\frac{1}{2}^+$	0.02	qg
E_6 Diquark	D	Triplet	0^+	0.004	qq
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
RS Graviton	G	Singlet	2^+	0.01	qq, gg
Heavy W	W'	Singlet	1^-	0.01	$q\bar{q}$
Heavy Z	Z'	Singlet	1^-	0.01	$q\bar{q}$
String	S	Mixed	Mixed	0.003-0.037	qg, $q\bar{q}$,gg

- Jets Algos: Particle Flow jets with cone 0.5 and 0.7 used for checks
- Special algo: WIDE JET implemented

Dijet Resonances at 1.0/fb

[CMS PAS EXO-11-015]

- **WIDE JETs** optimize dijet resonance mass resolution by recombining FSR into the two leading jets

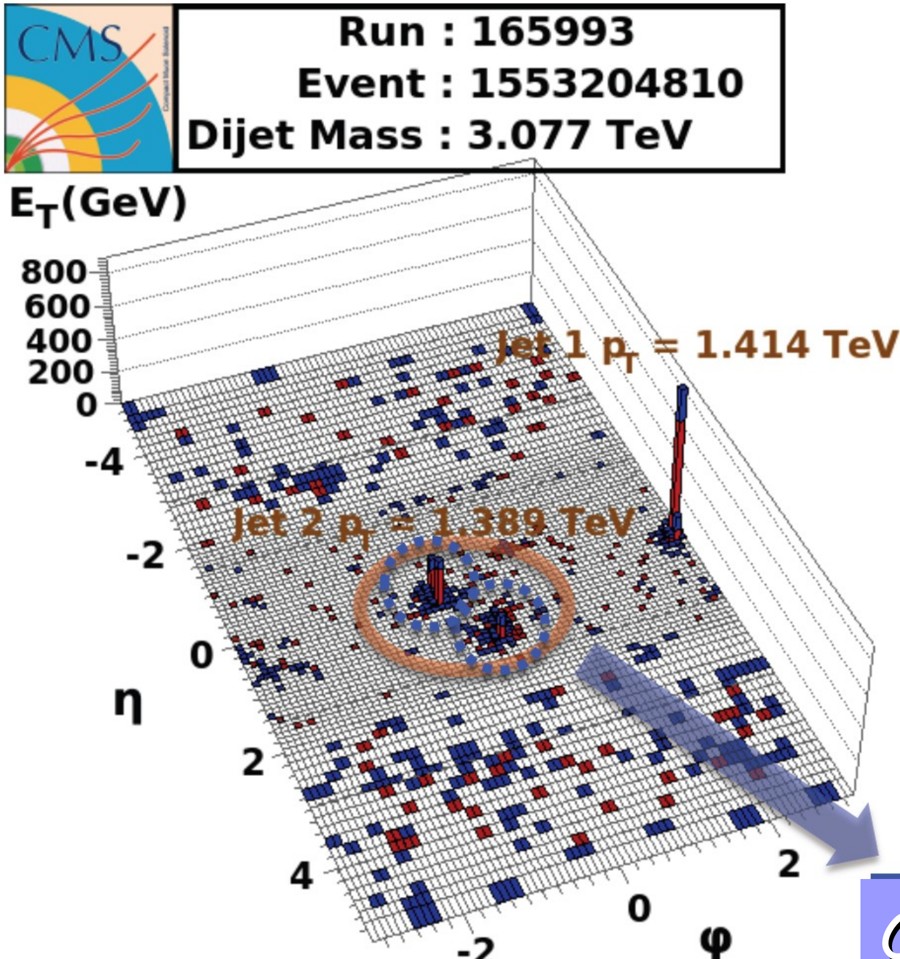


- WIDE JETs: build from clusters of Anti-K_T PF jets with cone R = 0.5
- Maximum size of WIDE JET: **R = 1.1**

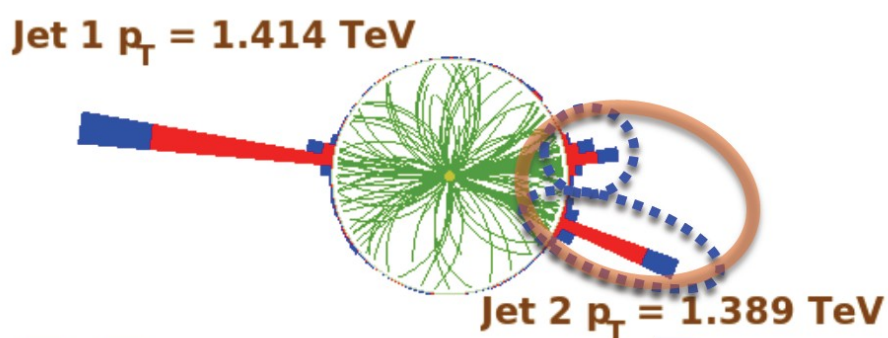
  is the best choice for these searches for qq, qg and gg resonances

Dijet Resonances at 1.0/fb

[CMS PAS EXO-11-015]



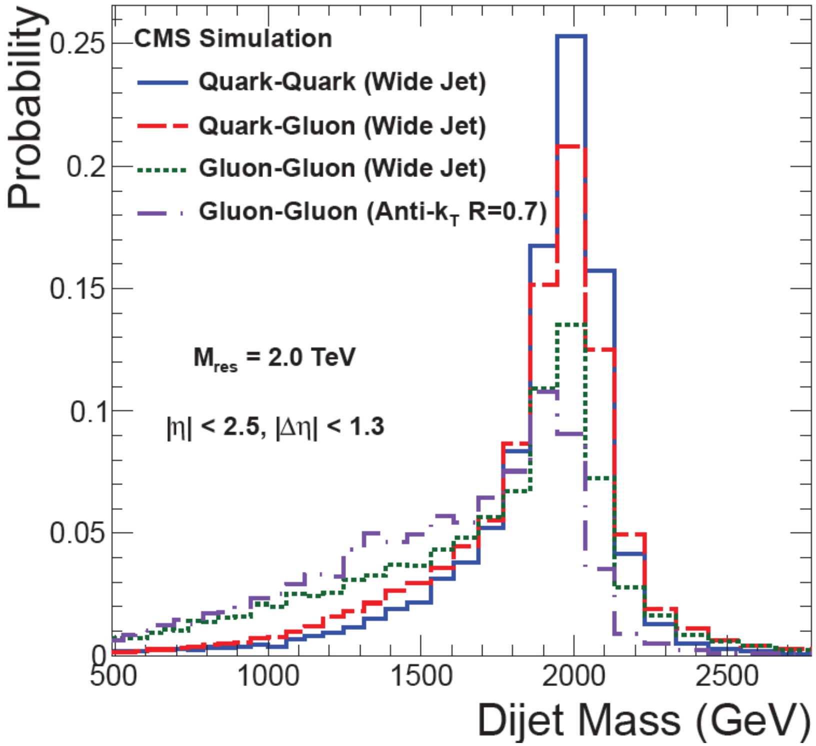
Dijet resonance candidate with high-pT jets

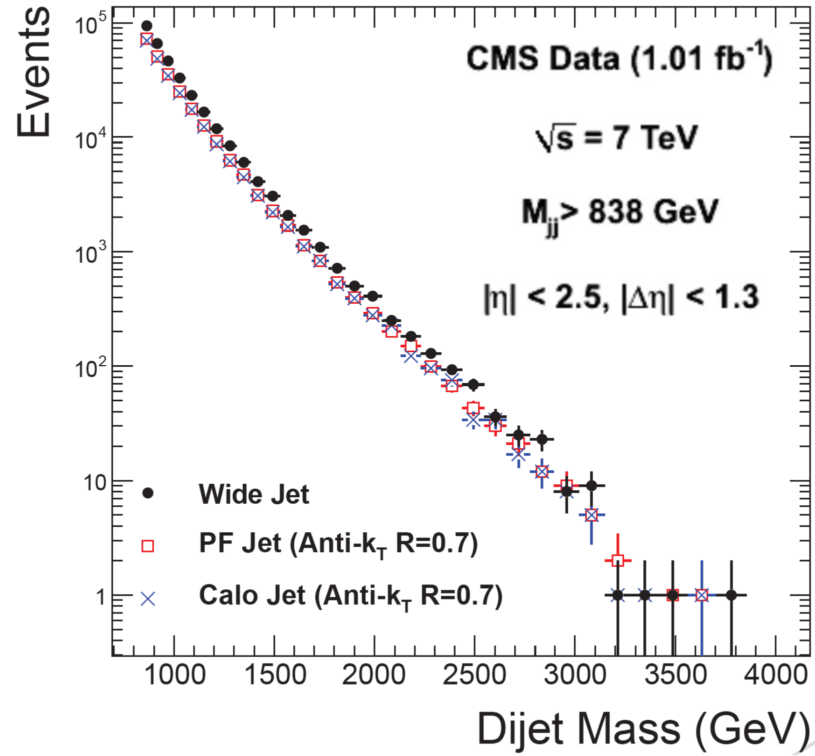


Combined into 1 WIDE JET

Dijet Resonances at 1.0/fb

[CMS PAS EXO-11-015]

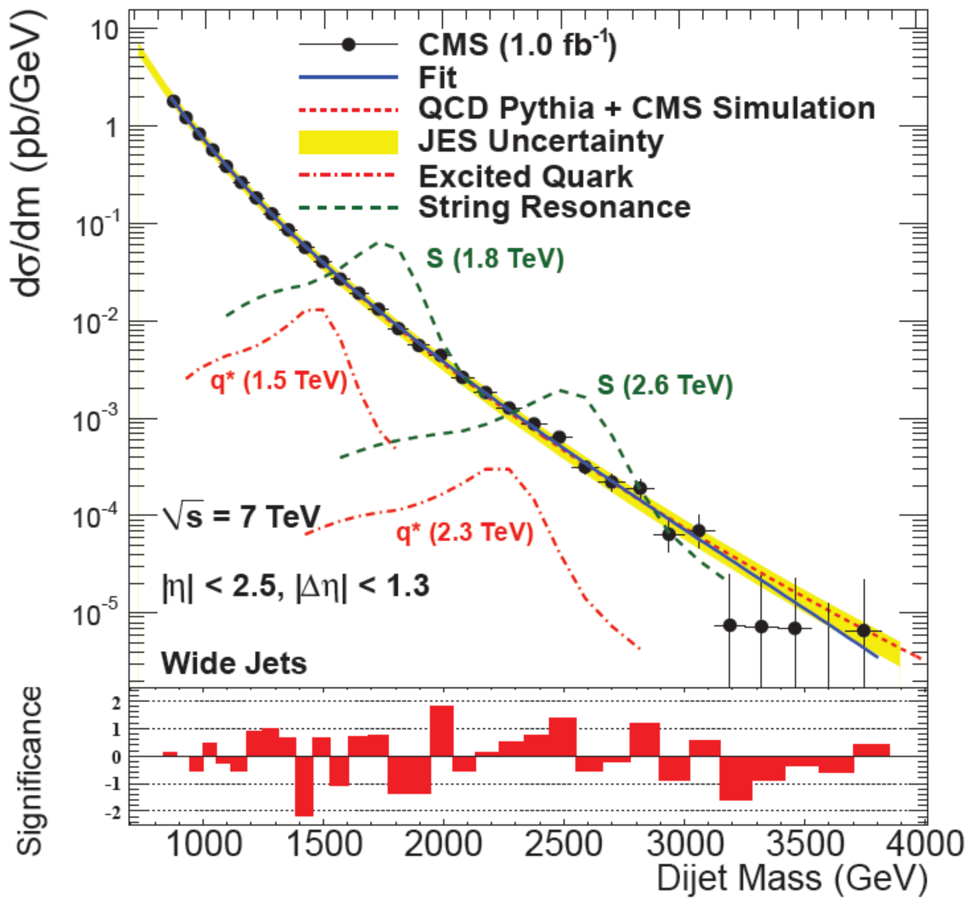




- Resonance shapes from CMS simulation:
  - Resonance decaying to qq, qg, gg
  - Width increases with number of gluons due to FSR
- Wide Jets shows better resolution than anti-k$_T$ 0.7, especially for gg
- Data Dijet Mass distribution from anti-k$_T$ 0.7 jets and Calo Jets agree
- Wide Jets collect more energy and have higher dijet mass

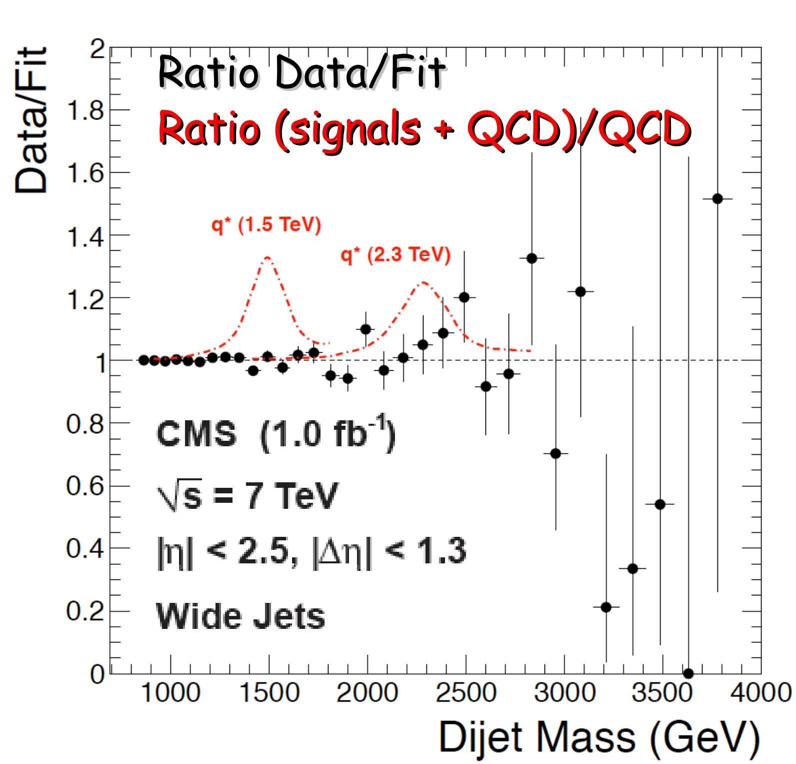
Dijet Resonances at 1.0/fb

[CMS PAS EXO-11-015]



- Data fitted with parametrization used also by CDF and ATLAS

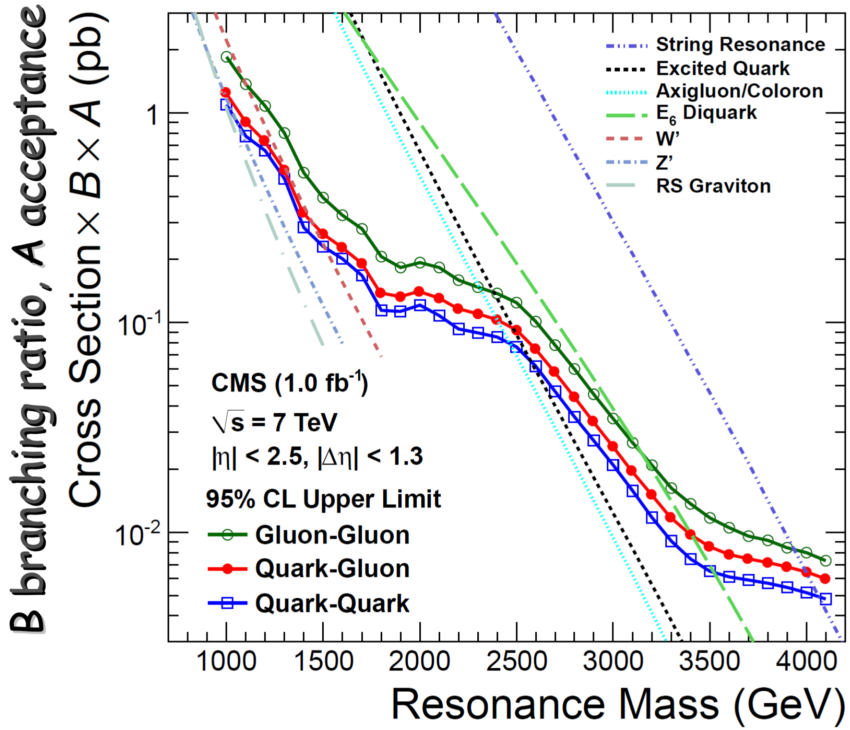
$$\frac{d\sigma}{dm} = \frac{P_0(1-m/\sqrt{s})^{P_1}}{(m/\sqrt{s})^{P_2+P_3\ln(m/\sqrt{s})}}$$

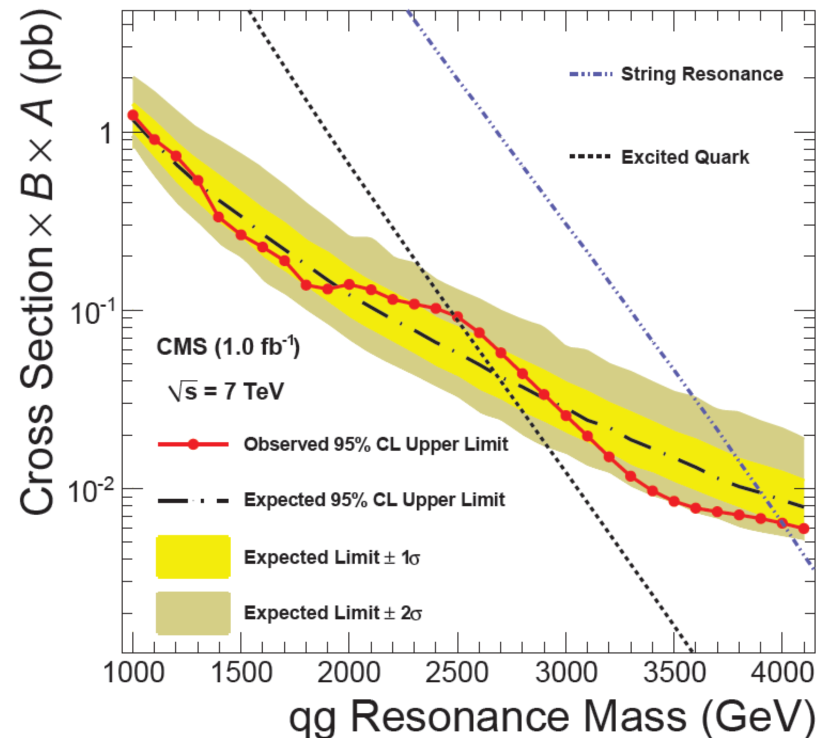


- Excellent fit agreement with data
- No evidence of new physics

Dijet Resonances at 1.0/fb

[CMS PAS EXO-11-015]





Exclusion limits depend on the model, but also on the resonance decay mode, because the increase of the width and the shift toward lower masses are enhanced with number of gluons in the final state

Limits

with Bayesian formalism

for dijets

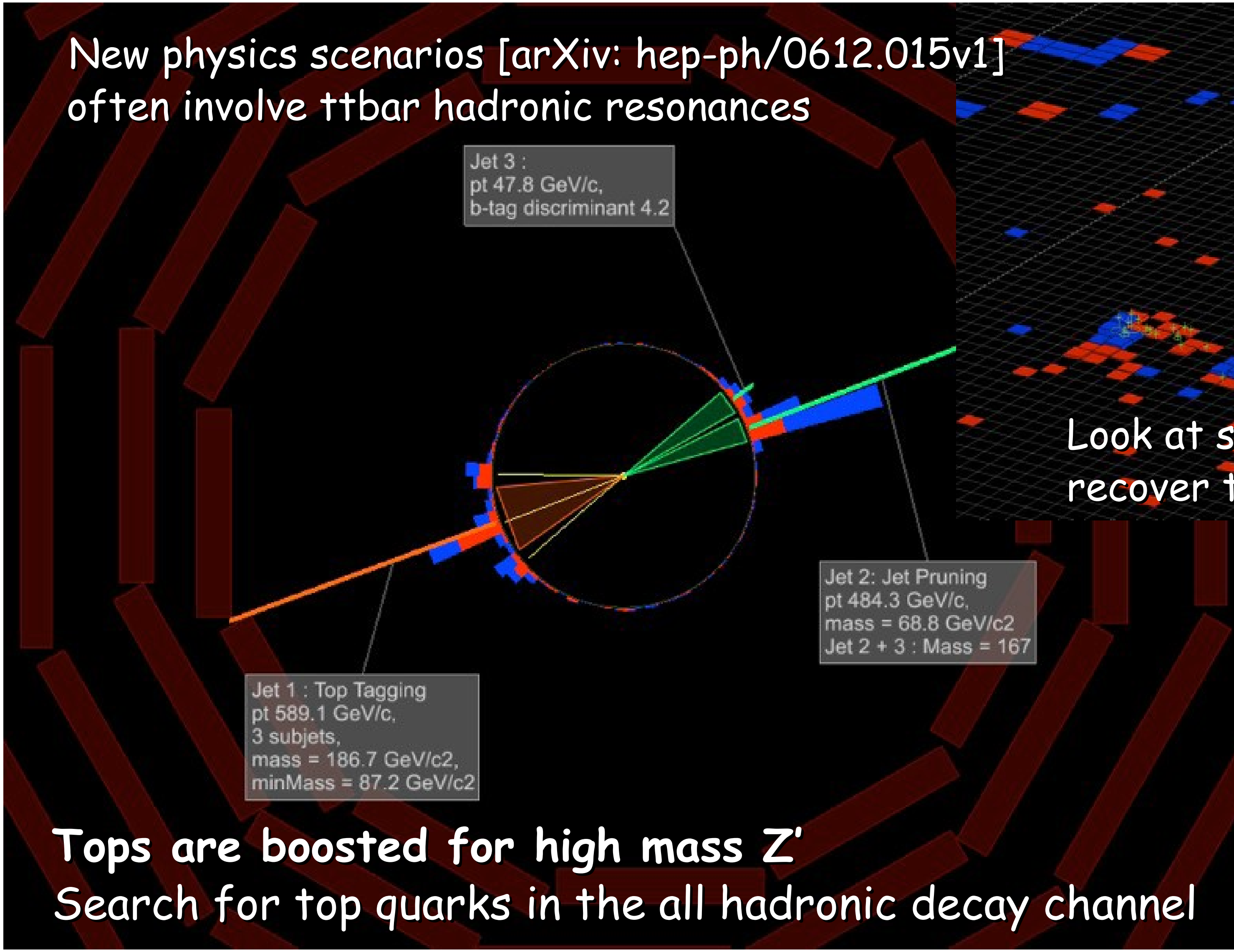
@ 1.0/fb

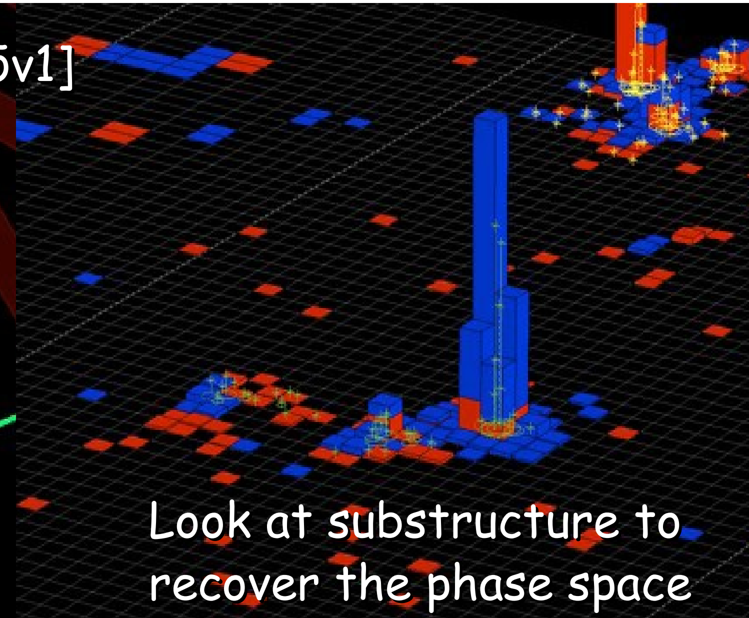
Model	Observed limit (TeV)	Expected limit (TeV)	Excluded at 95% CL (1 fb^{-1}) (TeV)
S	4.00	3.90	1.0 – 4.00
q*	2.49	2.67	1.0 – 2.49
A/C	2.47	2.66	1.0 – 2.47
D	3.52	3.28	1.0 – 3.52
W'	1.52	1.42	1.0 – 1.52
Z'	1.11	1.12	1.0 – 1.11
G	1.03	1.03	1.0 – 1.03

Z' → ttbar at 0.9/fb

[CMS PAS EXO-11-006]

New physics scenarios [arXiv: hep-ph/0612.015v1] often involve ttbar hadronic resonances





Look at substructure to recover the phase space

Tops are boosted for high mass Z'

Search for top quarks in the all hadronic decay channel

Z' → ttbar at 0.9/fb

[CMS PAS EXO-11-006]

- **Signature:**

  p p → Z' → (boosted) t tbar

Event selection:

- Trigger based on energetic jets with pT> 270 (300 GeV)

Event topology:

- Assume m_{ttbar} > 4x m_{top}
  - Create "boosted" final state (if E_T > 2x m_{top})

Concept:

recover information from boosted hadronic final states

Strategy:

Boosted hadronic objects have a mass scale and different kinematics than QCD

- Hemispheric topology

  Classify hemispheres by number of "total" jets:
  - "Type 1" : 1 fully merged jet
  - "Type 2": 1 partially merged jet, 1 non-merged jet

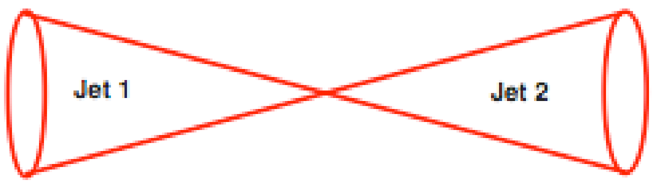
Background:

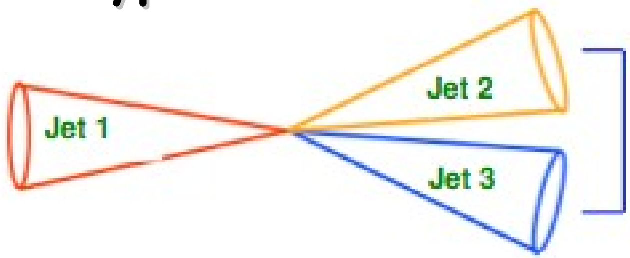
QCD multijet background, continuum SM ttbar production

Z' → ttbar at 0.9/fb

[CMS PAS EXO-11-006]

- Look at "Type 1 + 1" and "Type 1 + 2" events





- Jet pT > 350 GeV/c
- Both jets satisfy "top tagger" requirements
  (≥3 sub-jets with mass ~ m_{top}
  and pairwise mass ~ m_W)

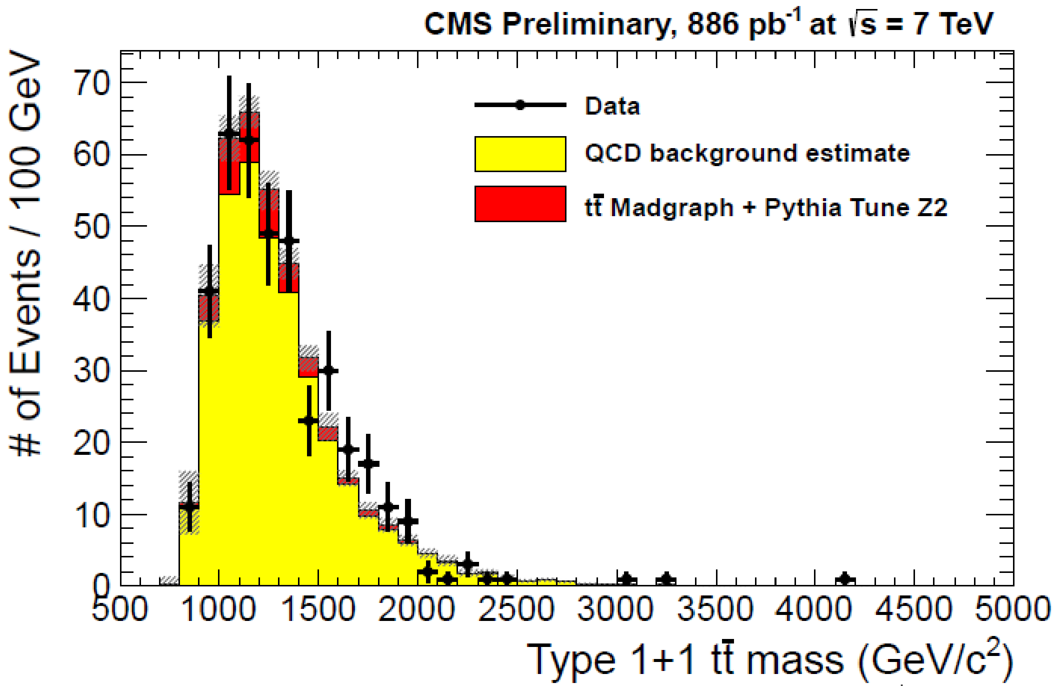
Jet reconstruction starts from "WIDE JET" (Cambridge-Aachen R = 0.8) algorithms and applies jet pruning to find sub-jets

- Veto Type "1 + 1" (< 1% overlap)
- Jet pT > 350, 200, 30 GeV/c
- Jet 1 (type 1 jet) satisfies "top tagger"
- Jet 2 (type 2 hemisphere) satisfies "W tagger" (2 sub-jets with similar mass and energy)
- Jet 3 (type 2 hemisphere) has no requirements

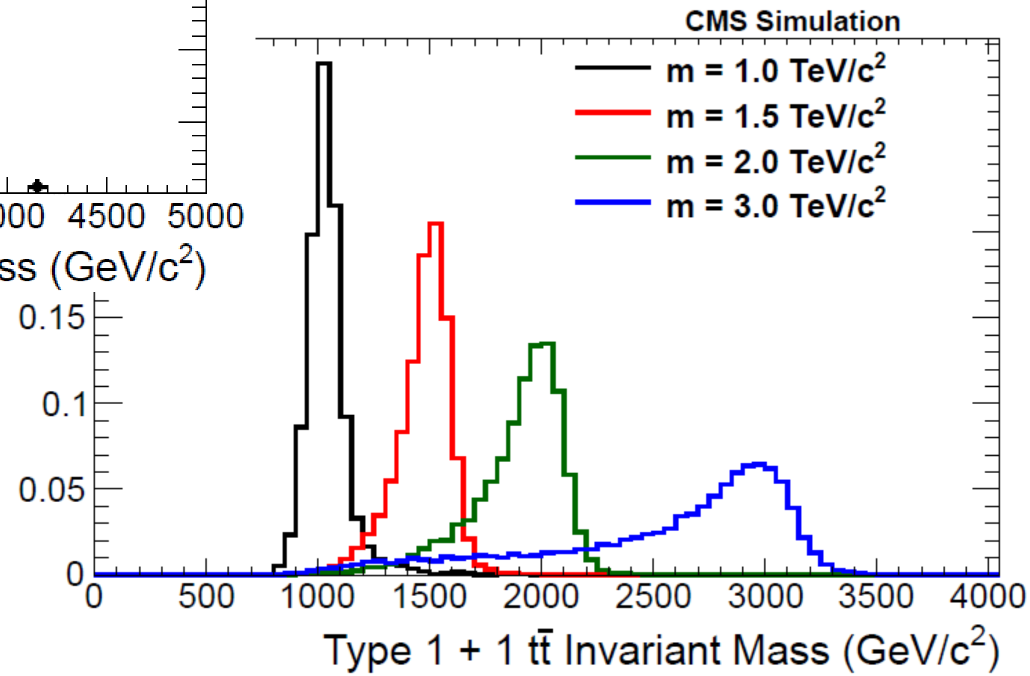
Z' → ttbar at 0.9/fb

[CMS PAS EXO-11-006]

- "Type 1 + 1"



Good agreement data vs QCD background estimate

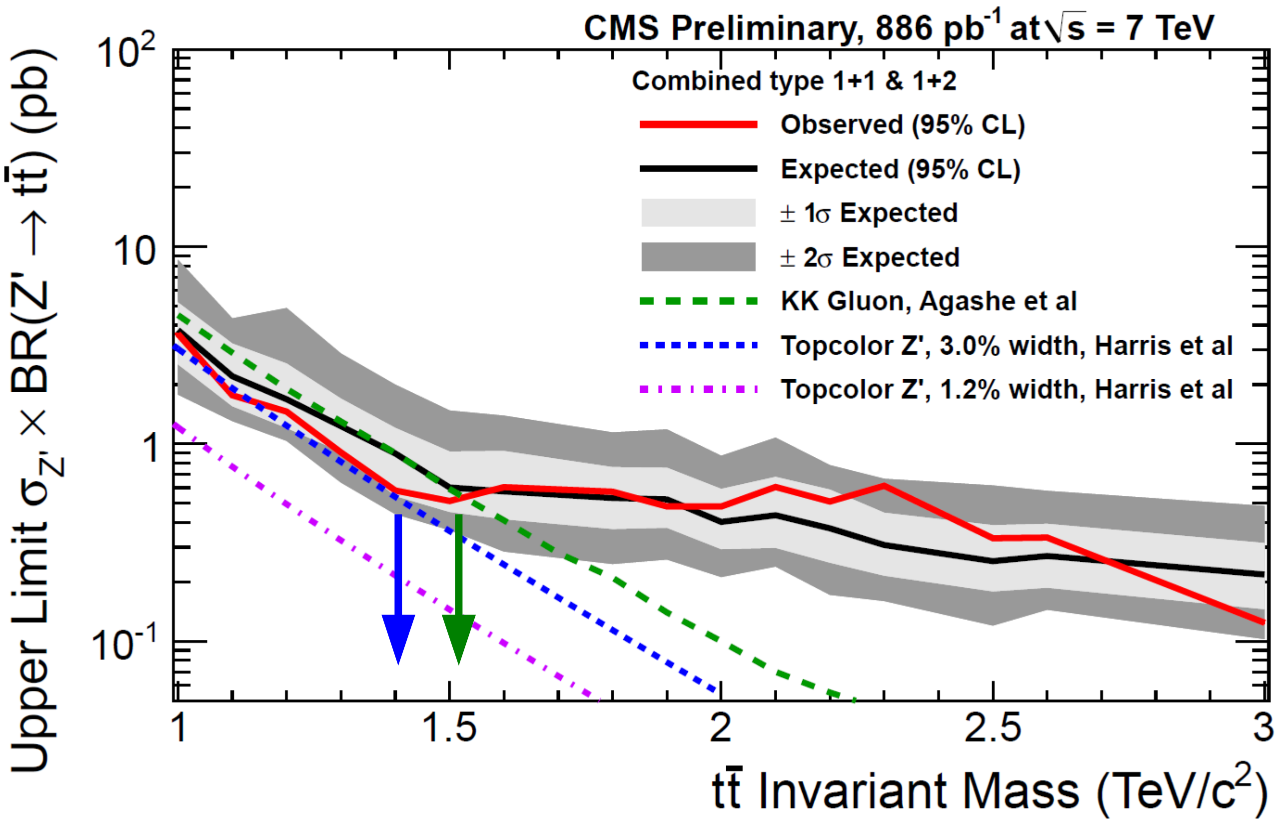


The same results for "Type 1 + 2"

Z' → ttbar at 0.9/fb

[CMS PAS EXO-11-006]

QCD background estimate from data (mistag method)



Excluded Topcolor Z' 3%: 1<M< 1.4 TeV

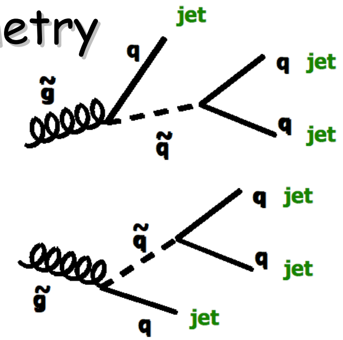
As well as KK-Gluon: 1<M< 1.5 TeV

Multijet Resonances at 35/pb

[CMS PAS EXO-11-001]

- **Multijet final states** are present in variations of technicolor models or R-Parity Violating Supersymmetry
- **Signature:**

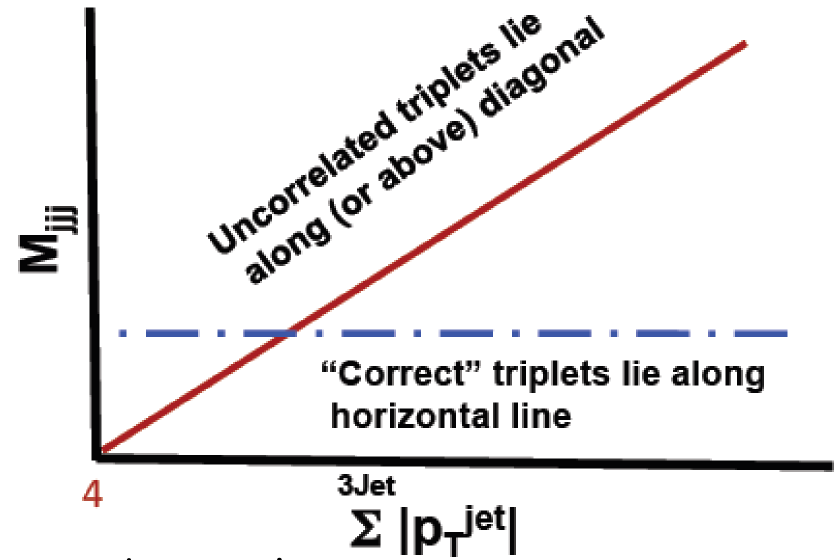
  $p\ p \rightarrow Q\ Q \rightarrow 3j + 3j$



20 triplet jet combinations from 6 jets

Event selection:

- Trigger based on HT > 100 (150) GeV
- At least **6 jets**
  PF jets with cone R=0.5,
  pT > 45 GeV and |η| < 3
- Offline HT of 6jets > 425 GeV



Background:

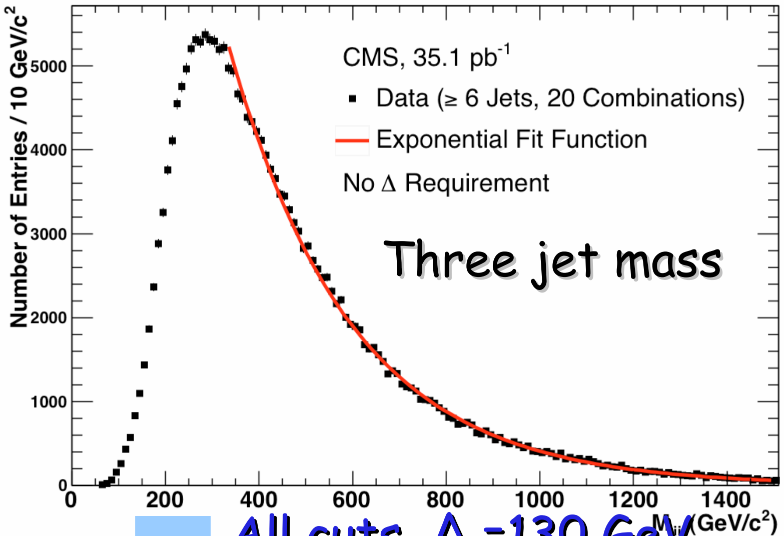
- Huge combinatorial background besides QCD background

Use a diagonal cut to remove combinatorial bkg as well as QCD bkg:

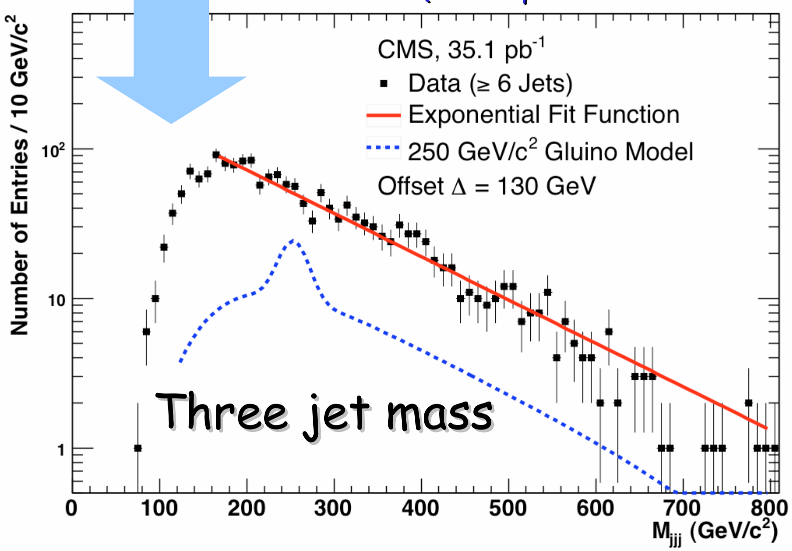
$mjjj < \Sigma_{i=1}^{3} |pT_i| - \Delta(\mathrm{Offset})$

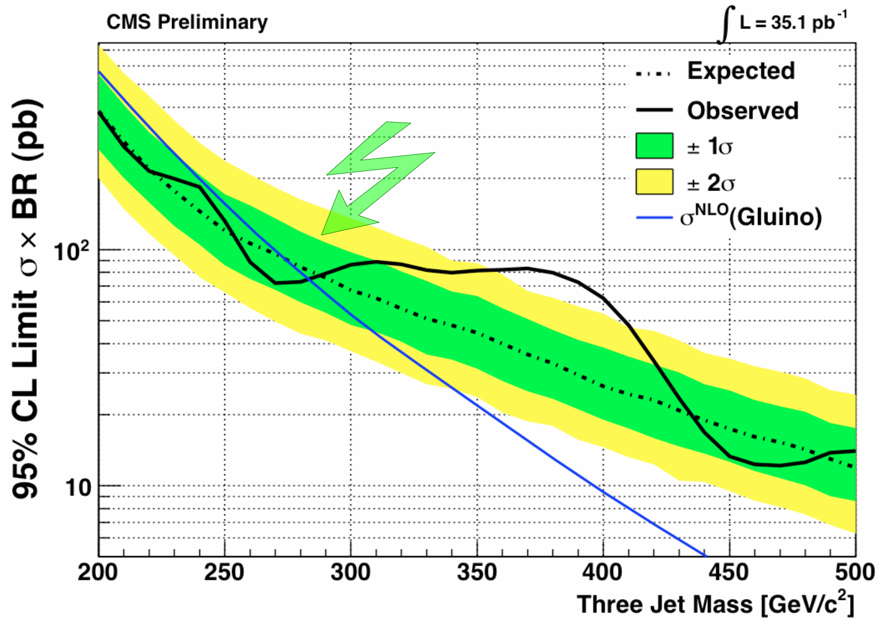
Multijet Resonances at 35/pb

[CMS PAS EXO-11-001]



All cuts, Δ =130 GeV
(for all gluino masses 200-500GeV)





No significant excess is observed

Excluded mass limit of RPV gluino at Bayesian 95% CL:

200 GeV < M < 280 GeV

Microscopic Black Holes at 1.1/fb

[CMS PAS EXO-11-071]

- The possibility of production of microscopic black holes in particle collisions has been predicted in models with low scale gravity

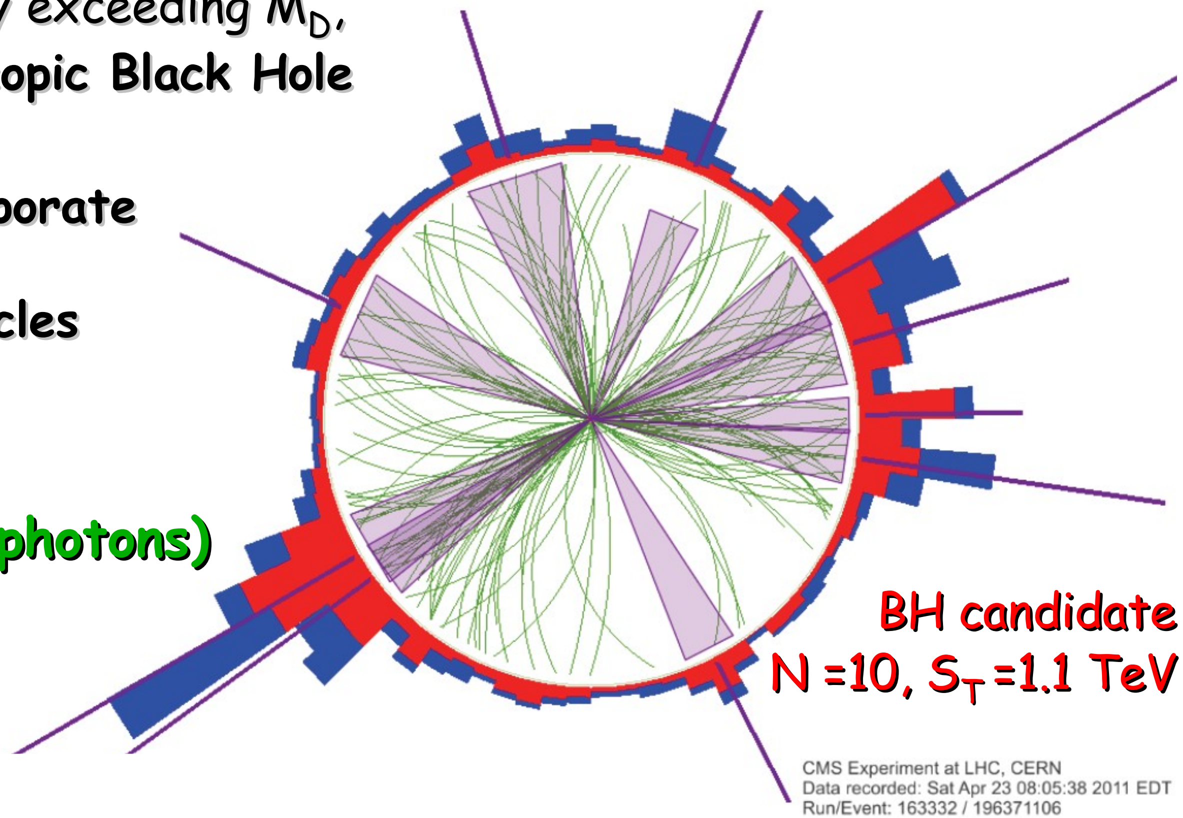
ADD ED, [Arkani-Hamed, Dimopoulos, Dvali, Phys. Lett. B 429, 263 & Phys. Rev. D59,086004]

- If the "true" Planck scale M_D is in the 1 TeV range, partons colliding with energy exceeding M_D, may **collapse into a Microscopic Black Hole**

- Once produced, the **BH evaporate** almost instantaneously by **emitting energetic particles**

- **Multiparticle signature**

  N objects (jets,leptons,photons)



BH candidate

N =10, S_T =1.1 TeV

Microscopic Black Holes at 1.1/fb

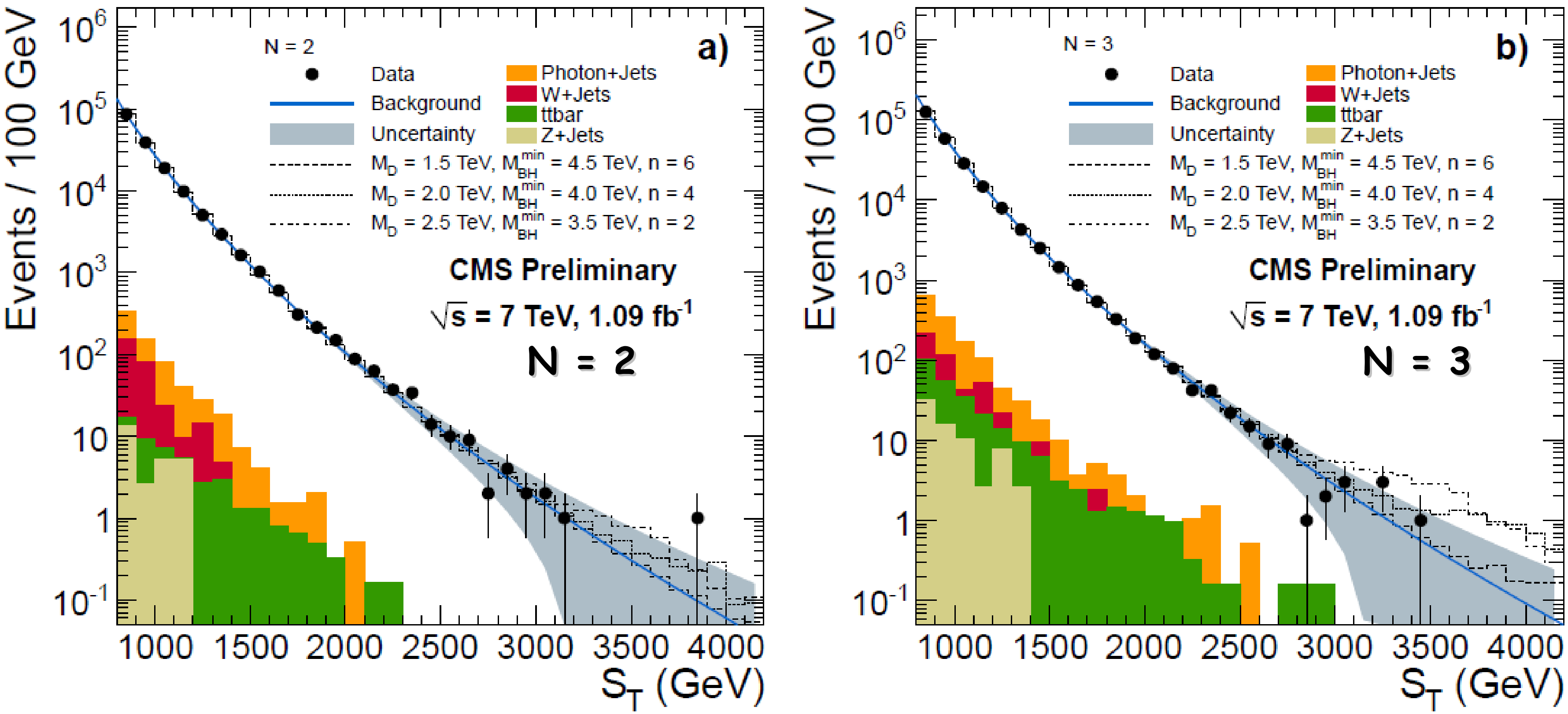
[CMS PAS EXO-11-071]

Analysis strategy:

- **Multiplicity (N)**
  Number of objects (jet,lep,γ) with pT>50 GeV in an event, excluding MET
- **S_T Scalar**
  p_T sum of all objects with ET>50 GeV + MET (if greater >50 GeV)
  S_T is almost independent of the final state multiplicity N
  => QCD bkg. estimation
- **Separation** ΔR (jet, lep/γ) > 0.5 and ΔR (lep/γ, lep/γ) > 0.3
- **Trigger** on total jet activity H_T in 350 - 550 GeV
  100% eff for S_T > 700 GeV

Microscopic Black Holes at 1.1/fb

[CMS PAS EXO-11-071]

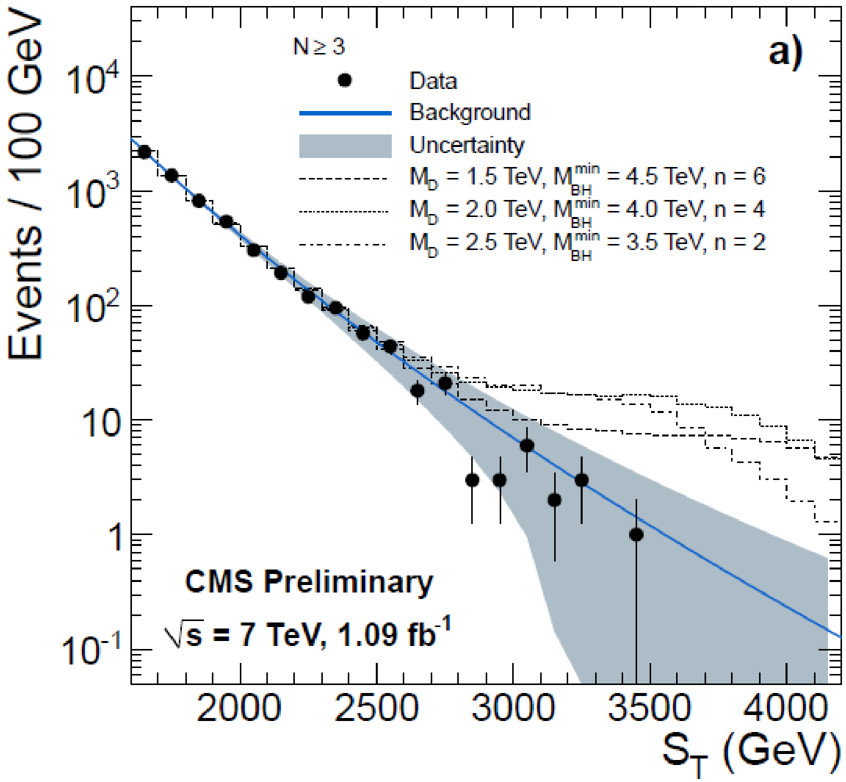


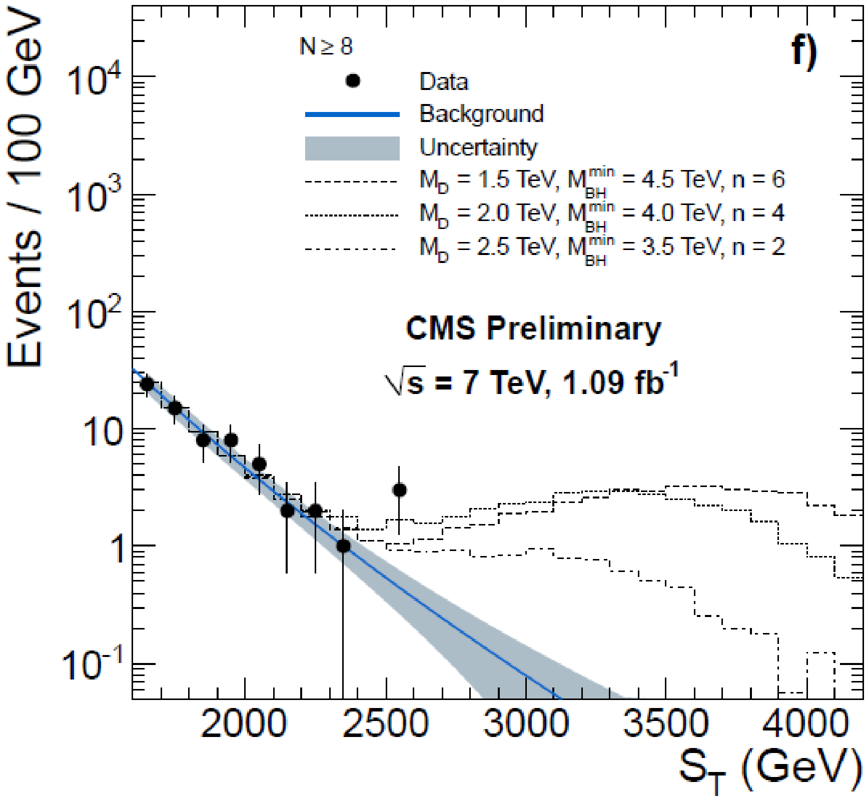
- Non-QCD backgrounds < 1% of data-driven bkg.
- There is no signal contamination in the fitting and normalization region
- Data-driven bkg. describes data consistently in exclusive multiplicities

Microscopic Black Holes at 1.1/fb

[CMS PAS EXO-11-071]

Inclusive multiplicities, for N ≥ 3 and N ≥ 8



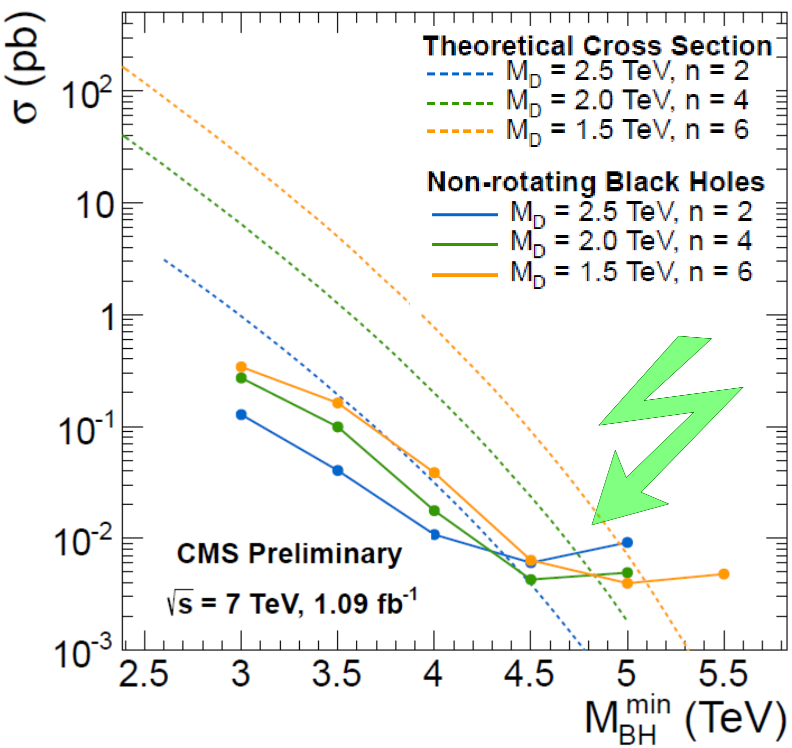


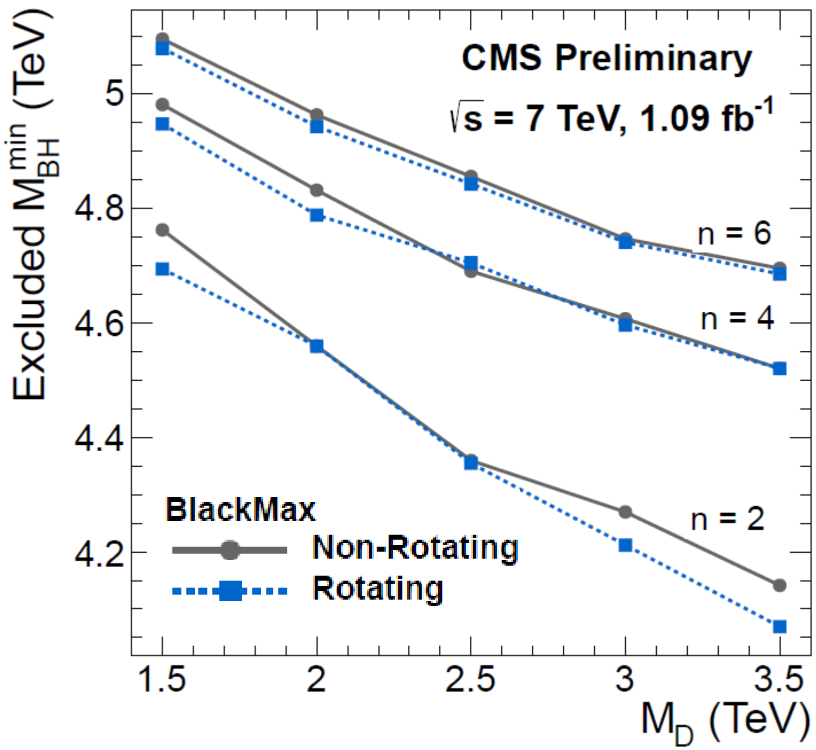
No excess in the signal

Microscopic Black Holes at 1.1/fb

[CMS PAS EXO-11-071]

95% CL limits on BH X-section and mass





Expected limits 4.4, 4.8, 5.1 TeV

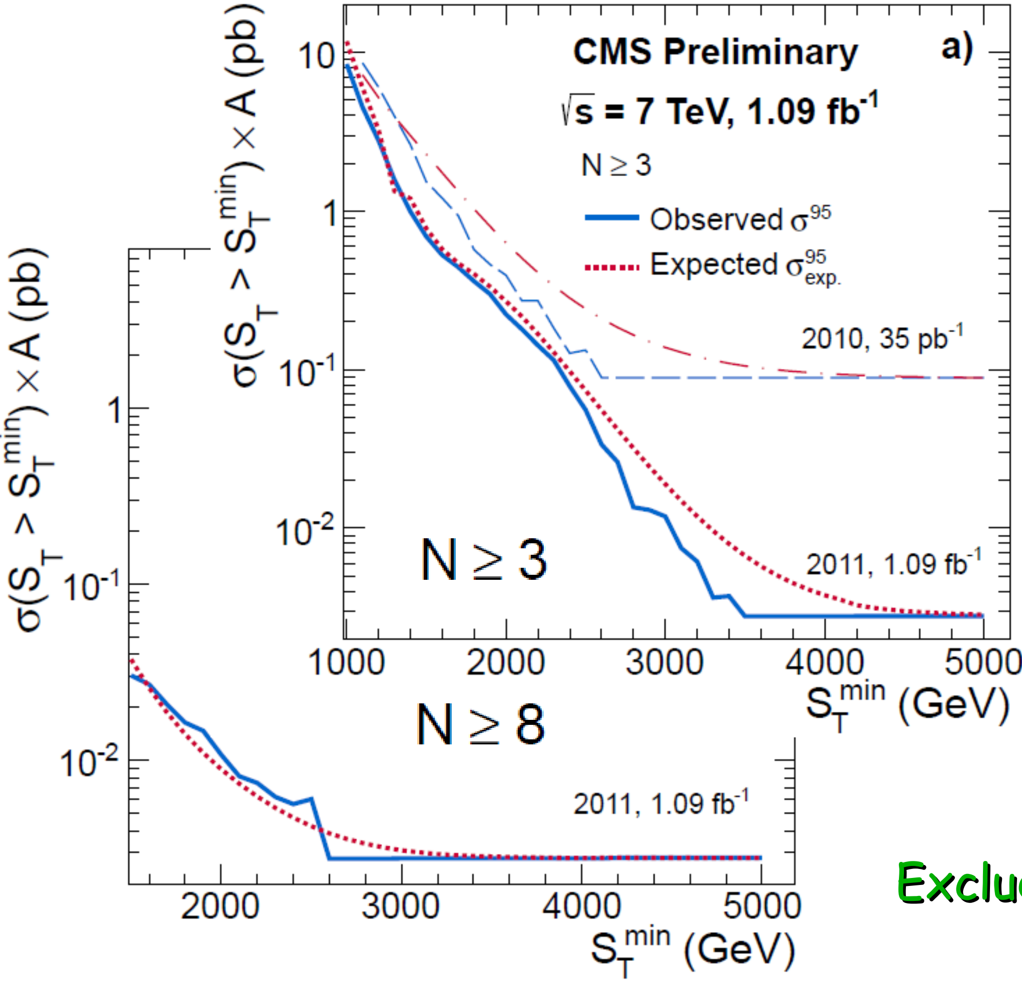
BH mass as a function of multidimensional Planck scale M_D

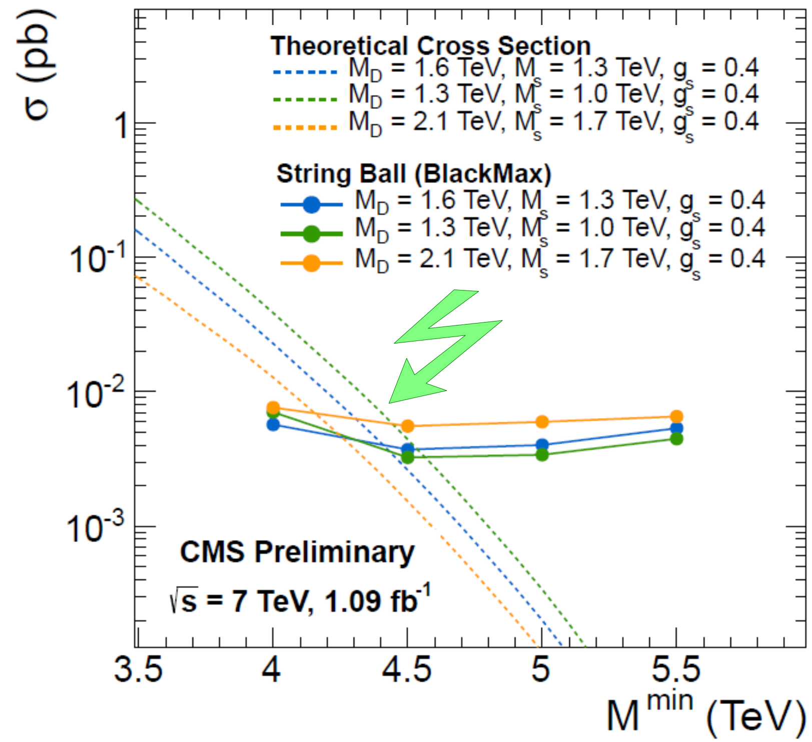
Microscopic Black Holes at 1.1/fb

[CMS PAS EXO-11-071]

Model independent 95% CL upper X-section limits

String balls - hypothesized precursors of the semiclassical black holes in highly quantum regime, when the mass of the object is close to the Planck scale





First direct limits on String Ball

Excluded min. M_{SB} = 4.0 - 4.5 TeV at 95% CL

Summary

- CMS multijet resonance searches have been presented based on 2011 data with about 1/fb
- No evidence for new physics yet
- Data significantly constrains many models of new physics
- 2011 data is quickly increasing, already collected > 2/fb

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- No evidence for new physics yet
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- 2011 data is quickly increasing, already collected > 2/fb
- "Nature loves to hide itself"...
  [Heraclitus of Ephesus]

References

CMS Analyses with the multijet signature:

[1] Search for ADD extra dimensions with a Monojet+MET signature,
CMS PAS EXO-11-059

[2] Search for New Physics in the Dijet Mass Spectrum,
CMS PAS EXO-11-015, arXiv:1107.4771v1, submitted to PRL

[3] Search for Z' to ttbar in high-mass all-hadronic channel,
CMS PAS EXO-11-006

[4] Search for Multijet Resonances in pp Collisions at sqrt(s) = 7 TeV,
CMS PAS EXO-11-001, arXiv:1107.3084v1, submitted to PRL,
update **EXO-11-060 @ 1.1/fb** coming soon

[5] Search for Black Holes in pp Collisions at sqrt(s) = 7 TeV with 1/fb Data Set,
CMS PAS EXO-11-071

Technical notes:

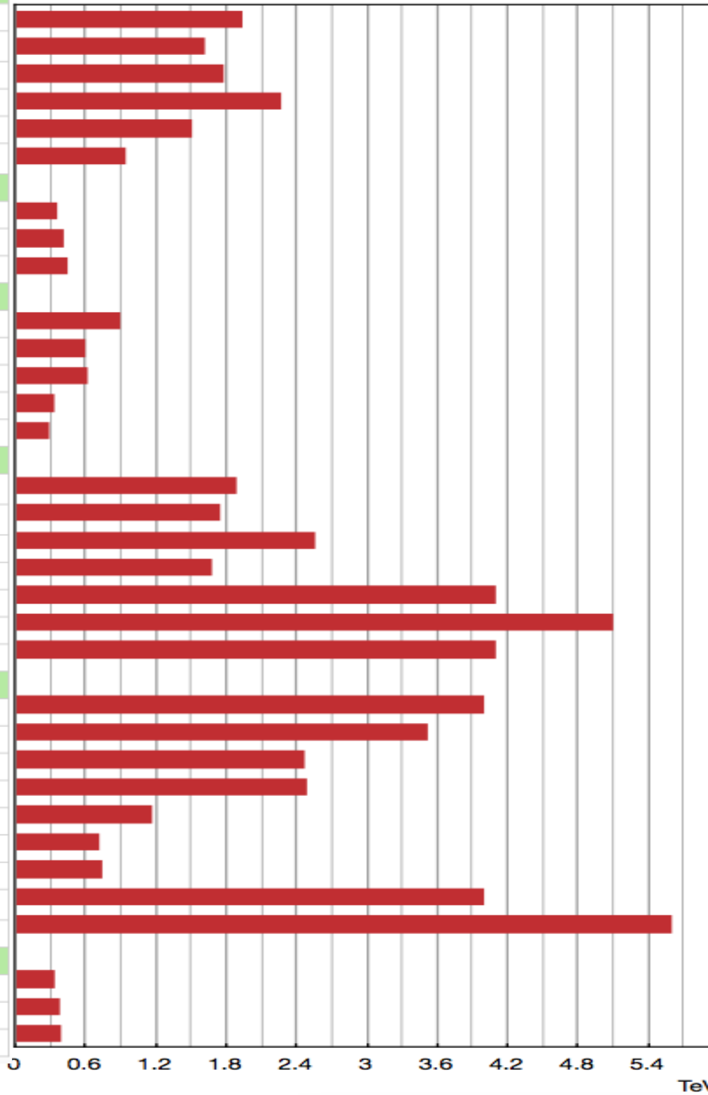
[6] Determination of the Jet Energy Scale in CMS with pp Collisions at sqrt(s) = 7 TeV,
CMS PAS JME-10-010

[7] Jet Energy Resolution in CMS at sqrt(s) = 7 TeV, **CMS PAS JME-10-014**

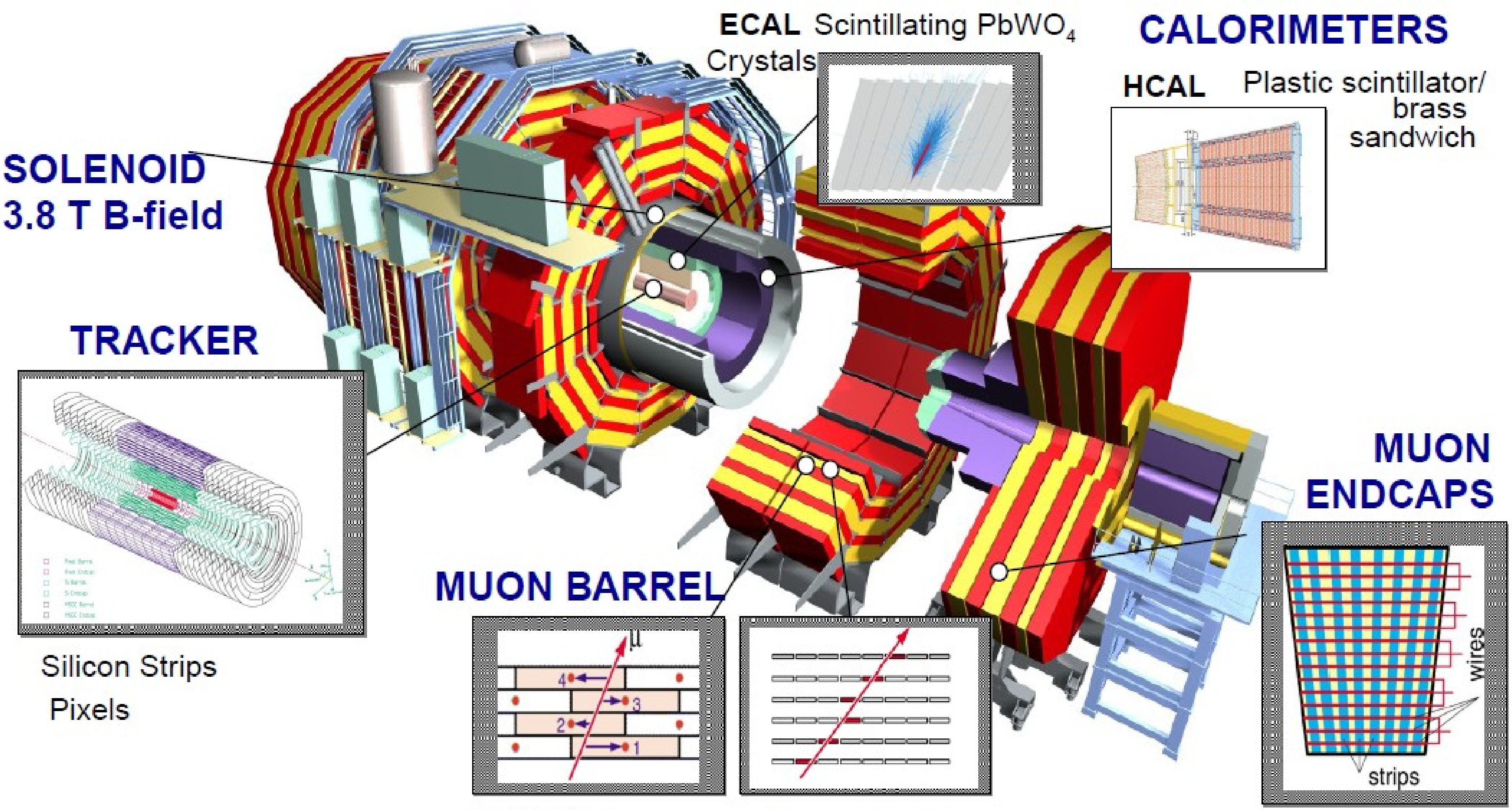
Backup slides

Exotica limits @ EPS

	Limits in TeV	
	Heavy Bosons	
Z'_{SSM} ll	1.94	2011
Z'_{Ψ} ll	1.62	2011
G_{KK} ll k/M = 0.1	1.78	2011
W' lv	2.27	2011
W' dijet	1.51	2011
G_{KK} $\gamma\gamma$ k/M = 0.1 (2010)	0.945	2010
	4th Generation	
$M_{b'}$, b' $\Rightarrow$ tW (2010)	0.361	2010
$M_{t'}$, t' $\Rightarrow$ tZ (100%)	0.417	2011
$M_{t'}$, t' $\Rightarrow$ bW (100%), l+jets	0.45	2011
	Heavy Stable Particles	
M_{gluino}, HSCP	0.899	2011
M_{gluino}, Stopped Gluino	0.601	2011
M_{stop}, HSCP	0.620	2011
M_{stop}, Stopped Gluino	0.337	2011
M_{stau}, HSCP	0.293	2011
	Large Extra Dimensions	
M_s, $\gamma\gamma$, GRW (2010)	1.89	2010
M_s, $\mu\mu$, GRW (2010)	1.75	2010
M_D, monojet, n_{ED} = 2 (2010)	2.56	2010
M_D, monojet, n_{ED} = 6 (2010)	1.68	2010
M_{BH}, rotating, M_D=3.5 TeV, n_{ED} = 2	4.1	2011
M_{BH}, non-rot, M_D=1.5 TeV, n_{ED} = 6	5.1	2011
String Ball M, M_D=2.1, M_s=1.7, g_s=0.4	4.1	2011
	Compositeness and Contact Interactions	
String Resonances	4.0	2011
E_6 diquarks	3.52	2011
Axigluon/Coloron	2.47	2011
q* , dijet	2.49	2011
q* , boosted Z	1.17	2010
e*, Λ = 2 TeV	0.720	2010
μ*, Λ = 2 TeV	0.745	2010
C.I. Λ , dijet mass (3 pb^{-1})	4.0	2010
C.I. Λ , X analysis	5.6	2010
	LeptoQuark	
LQ1, β=0.5 (2010)	0.340	2010
LQ1, β=1.0 (2010)	0.384	2010
LQ2, β=1.0 (2010)	0.394	2010



Compact Muon Solenoid



Azimuthal angle: ϕ
Polar angle: θ
Pseudorapitidy: $\eta = -\ln\tan(\theta/2)$

Monojet + MET at 1.1/fb

[CMS PAS EXO-11-059]

Monojet selection

Requirement	W+jets	Z(νν)+j	Z+j	$t\bar{t}$	t	QCD	Total BG	Data
$E_T^{miss} > 200$ GeV, jet cleaning	13689	5182	1103	2837	213	2588	25613	24428
$p_T(j_1) > 110$ GeV/c, $\|\eta(j_1)\| < 2.4$	13080	4936	1056	2601	195	2558	24425	23623
$N_{Jets} \leq 2$	8553	3686	725	299	46.4	768	14078	14544
$\Delta\phi(j_1, j_2) < 2.5$	7448	3446	659	253	40.0	19.2	11865	12345
Lepton Removal	2174	3328	16.1	47.9	6.7	0.5	5573	5965
$E_T^{miss} > 250$ GeV	639	1192	4.0	14.1	1.9	0.5	1851	1930
$E_T^{miss} > 300$ GeV	200	483	0.9	4.6	0.6	0.1	689	708
$E_T^{miss} > 350$ GeV	67.8	217	0.3	1.7	0.2	0.1	288	293
$E_T^{miss} > 400$ GeV	36.2	105	0.1	0.9	0.1	0.1	142	151

Monojet data sample and analysis cuts, with luminosity-normalised LO MC

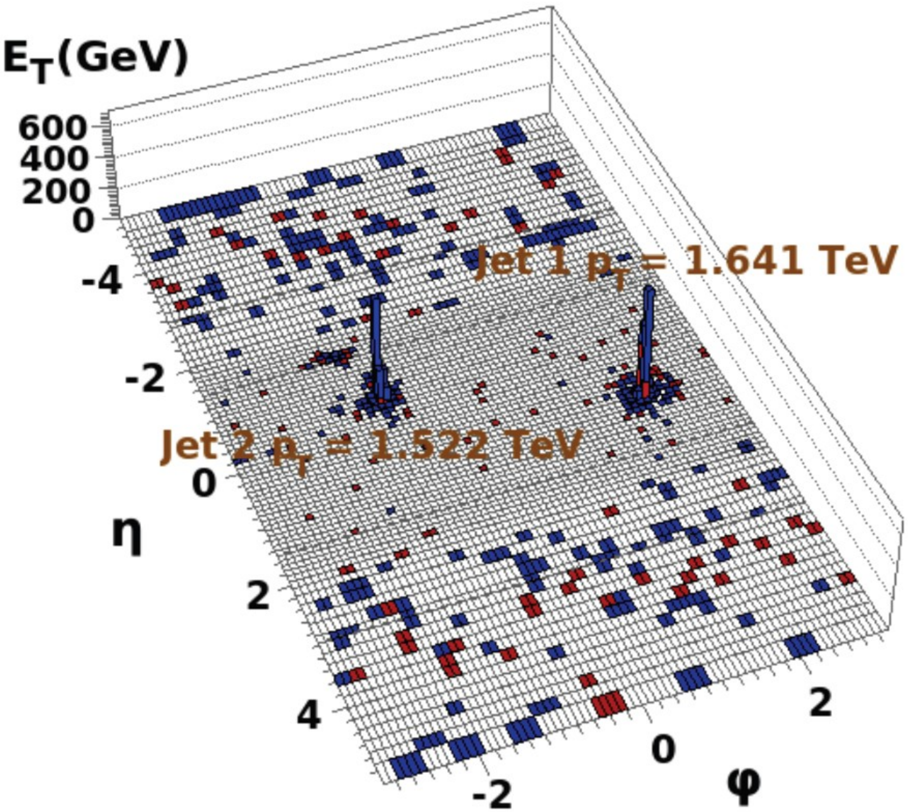
Lepton Removal:

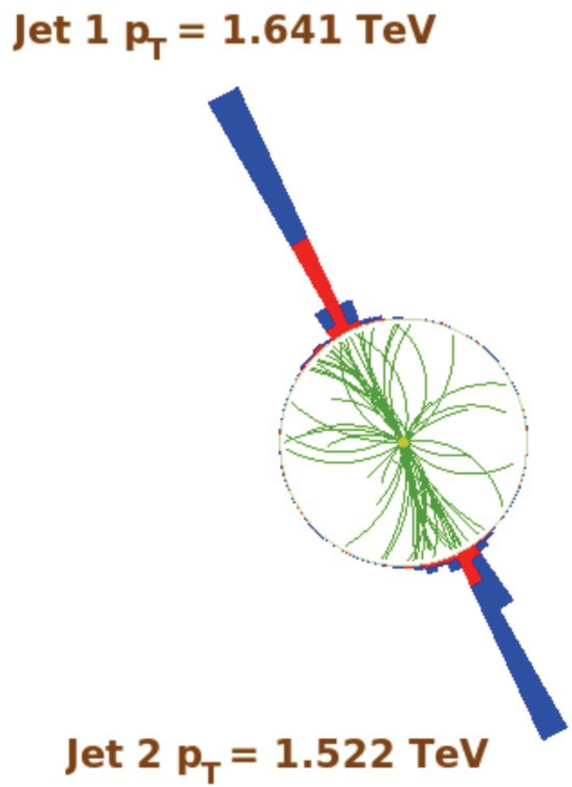
events with isolated muons or tracks for pT(e,μ) > 20 GeV are eliminated

Dijet Resonances at 1.0/fb

[CMS PAS EXO-11-015]

Run : 166895
Event : 367873378
Dijet Mass : 3.835 TeV

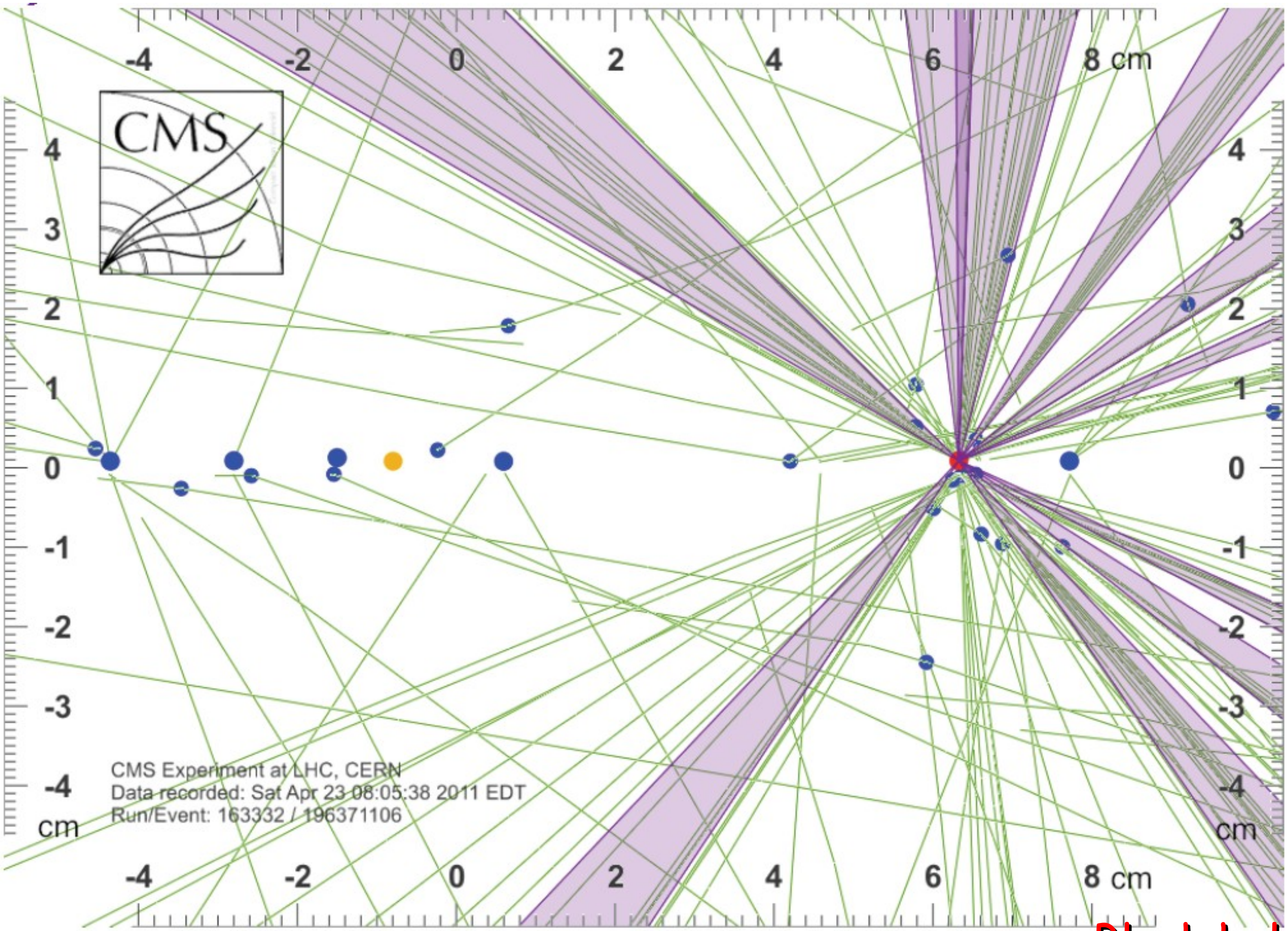




- Highest dijet event with well balanced dijets

Microscopic Black Holes at 1.1/fb

[CMS PAS EXO-11-071]



Black hole candidate

$N = 10$, $S_T = 1.1$ TeV

All jets are form the same primary vertex (red dot).